TAMPEREEN TEKNILLINEN YLIOPISTO
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AUTOMATED OPTICAL INSPECTION IN AUTOMOTIVE ASSEMBLY LINE

Master of Science Thesis

Examiners: Professor Jose L. Martinez Lastra, Dr. Jani Jokinen
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ABSTRACT

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Quality is becoming more important instrument of competition in industry of technology. A product with decent quality sells well in the market and increases the image of the company. In addition the quality increases profitability. The aim of this work is to design an automated quality inspection gate before test run. Quality inspection is already conducted by a human worker but objective is to expand quality inspection with a robot and smart camera. The work presents different kind of inspection systems from manufacturing industry. The system requires a robot in order that a smart camera can be moved easily and all camera angles can be reached. The system could be designed to be part of manual quality gate and that's why this work presents light weight robots which can co-operate with a human without external safety equipment. One of the objectives is also to find which features are important and how they could be inspected automatically.

The work is divided into two parts: Literature studies examine properties and use of quality inspection in manufacturing industry. In addition suitability of different kind of machine vision systems for quality inspection is compared. Light weight robots are more advanced robots than classical industrial robots. The work introduces the structure and control principles of light weigh robots and why it is safe to work with light weight robots without external safety equipment. The second part is application part which presents quality inspection examples and methods how the features are inspected. Images taken with a smart camera show the difference between a right and wrong product. A model created with a 3D-software ensures that a robot can reach all camera angles.

The research shows how the optimal solution can be reached with the co-operation of a robot and a human. A smart camera is untiring inspector which can detect faults that a human eye can detect easily. However, a smart camera can't detect everything or it is more feasible to inspect some features manually. By combining the strengths of machine vision and human vision the optimal application can be reached.

TIIVISTELMÄ

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Laatu on yhä tärkeämpi kilpailutekijä teknologiateollisuudessa. Sen lisäksi, että laadukas tuote myy hyvin markkinoilla ja parantaa yrityksen imagoa, parantaa laatu myös kannattavuutta. Tämän työn tavoitteena on suunnitella automaattinen laaduntarkastuspiste ennen koekäyttöä. Laaduntarkastusta suoritetaan myös ihmisen toimesta, mutta tavoitteena on laajentaa tarkastusta robotin ja älykameran avulla. Työssä esitellään kokoonpanoteollisuudessa yleisesti käytettyjä tarkastusmenetelmiä. Tarkastuspiste vaatii robotin, jotta älykameraa pystytään liikuttelemaan haluttuihin pisteisiin oikean kuvakulman saavuttamiseksi. Tarkastuspiste on mahdollista suunnitella manuaalisen tarkistuspisteen yhteyteen, jonka vuoksi työssä esitellään kevyitä robotteja, jotka pystyvät toimimaan yhteistyössä ihmisen kanssa ilman turva-aitoja ja valoverhoja. Tavoitteena on myös löytää laadun kannalta tärkeimpiä tarkastuskohteita ja selvittää millä keinoin ne pystyttäisiin tarkastamaan automaattisesti.

Työ jakaantuu kahteen osaan: Kirjallisuustutkimusosassa selvitetään teollisuudessa käytettyjen laaduntarkastusmenetelmien ominaisuuksia ja käyttötarkoituksia. Tämän lisäksi vertaillaan erilaisten näköjärjestelmien soveltuvuutta laaduntarkastukseen. Kevyet robotit ovat kehittyneempiä kuin perinteiset teollisuusrobotit. Työssä esitellään näiden robottien rakennetta ja ohjausperiaatteita, joiden ansiosta turvallinen yhteistyö ihmisen kanssa on mahdollista. Sovellusosassa esitellään valittuja laaduntarkastuskohteita ja menetelmiä, joilla ne voitaisiin tarkastaa. Kohteista älykameralla otetut kuvat näyttävät eron oikean tuotteen ja väärän tuotteen välillä. 3D-ohjelmiston avulla luodun mallin perusteella varmistutaan robotin ulottuvuuden riittävyydestä kaikkiin kuvauspisteisiin.

Tutkimus osoittaa, kuinka robotin ja ihmisen välisellä yhteistyöllä on mahdollisuus päästä parhaimpaan lopputulokseen. Älykamera robotin tarttujana on väsymätön tarkistaja ja pystyy havaitsemaan virheitä, joita ei ihmissilmällä pysty helposti havaitsemaan. Älykameran tarkastuskohteet ovat kuitenkin rajalliset ja ihminen pystyy havaitsemaan tietyn tyyppiset virheet helpommin kuin älykamera. Yhdistettynä molempien vahvuudet päästään laaduntarkastuksessa parhaimpaan mahdolliseen lopputulokseen.

PREFACE

Working at AGCO Power has had a significant impact on my course selection and studies at Tampere University of Technology. It also affected my bachelor and master thesis topics as machine vision and automatic quality inspection were under development at AGCO Power's manufacturing lines. I would like to acknowledge the support of the AGCO Power's personnel who have contributed in this thesis. I'm also grateful to my tutor Dr. Jani Jokinen who encouraged me to work on this topic and spent time guiding my master thesis.

In Tampere, Finland, on 1st February 2015

Tarmo Rouhiainen

CONTENT

TERMS AND ABBREVIATIONS

AOI – Automated optical inspection
ABS – Acrylonitrile Butadiene Styrene
CAD – Computer-aided design
CAM – Computer-aided manufacturing
CWS – Collaborative Work Space
DLR – The German Aerospace Center
DoF – Degree of freedom
Euro NCAP – European New Car Assessment Programme
HIC – The Head Injury Criterion
HRC – Human-Robot Collaboration
Keko – Assembly process control software
LWR – Light-weight robot
RA – Risk Assessment
SPC – Statistical Process Control

1 INTRODUCTION

Companies around the world have faced markets with competition that is getting harder all the time. One way to achieve competitive advantage over other competitors is provide better quality. Producing products which are flawless is one way to improve quality. This work presents applications used in manufacturing industry to inspect quality using robots and smart cameras. Some features can be easily measured with machine vision systems while those features could be boring to check on the long run or they couldn't be measured with human eye without external tools. However some features can be checked more easily with human eye than using machine vision. One of the objects in this work is study light weight robots and explains why they can co-operate with a human without external safety equipment. Studying light weight robots points out they can share the workspace with humans. The last chapter of this thesis deals with an application where a light weight robot and smart camera could be used to inspect assembled diesel engine.

1.1 Drivers for quality inspections

Companies have several reasons why they should be improving quality. As the competition is really high in automotive industry improving quality can provide several advantages. For example customers are more likely to buy a product again if it had fewer flaws. Better quality often means less quality costs. Quality inspection is used to ensure that a product is correctly assembled and correct parts have been used. Early quality inspection can reduce reworking time as amount of parts disassembled is minimal. The further the product goes in the process the greater the impact will be on quality costs. For example it is easier and cheaper to fix the product at a factory than at a customer's place and certain missing parts at test run could have expensive consequences.

1.2 Introduction of the AGCO Power

AGCO Power has a long tradition of producing diesel engines. It has operated nearly 70 years in a plant located in Linnavuori in the town of Nokia. The production technology was renovated in 2005-2007. The production technology varies from manual assembly to fully automated applications.

AGCO Power, formerly known as Sisu Diesel and AGCO SISU POWER, was renamed by the US AGCO Corporation. AGCO has invested tens of millions of euros and made the company one of the world's leading producers of diesel engines. The annual production volumes vary between 30,000 – 40,000 engines and the number of employees is approximately 800. Many of the world's leading manufacturers of tractors and other farm machinery uses engines made by AGCO Power. It also used for a large number of other applications around the world.

AGCO Power is a leading engine manufacturer in agricultural machines with its new Citius series Common Rail engines that meet the latest European and North American emission standards.

1.3 Background and objectives

The current assembly line is a serial line where the engine is assembled by robots and humans. The work done by robots is checked with machine vision systems and other tools with in-built intelligent error monitoring functions. The line has one quality gate where some important features are checked by a human before the engine goes to the testing phase. Diesel engines consist of hundreds of parts without speaking of different kind of variations. At each phase a worker has a screen in which the list of required parts is shown. In spite of detailed instructions and training some mistakes occur occasionally. Workers chance their workstation regularly because of repetitive and routine work tasks. Because of repetitive work concentration might become exhausted and possibility of an error increases. As a result a wrong part might be installed.

In theory a defect should be fixed before a product proceeds in the process. However fixing the product can stop the whole production process. Most of the features can be fixed at a quality gate without disassembling other parts. Because of that most of the features could be inspected at quality gate.

A worker working at quality gate don’t have time to check all parts. The time is used to inspect most common errors for the engine type and most critical errors that could cause problems in the testing phase. Checking all the features would be too repetitive, exhausting and would require too much time. With automated inspection a human worker could focus on the most important features.

As a background study this thesis takes a look at automatic quality inspecting applications and light weight robots. The objective is to design an automatic quality inspection system. The last chapter presents a solution where a light weight robot equipped with a smart camera could assist a human worker at quality gate in shared work environment. The thesis doesn’t present a fully implemented application but it shows captured images and simulations that the designed system could be implemented successfully.

1.4 Thesis outline

The thesis begins with a theoretical approach while advancing slowly to a practical part. The second chapter is all about automatic quality inspection applications. Introducing several industrial applications and comparing them among each other aims to create perspective and the reader should have an idea what kind of applications exist in modern manufacturing industry.

The third chapter studies light weight robots. The beginning of the chapter explains the structure of a light weight robot, its control theory and why they can be considered safe and collaborative with a human. The end of the chapter moves closer to practical part as light weight robots are compared to classical industrial robots. The comparison includes also some examples in AGCO Power's assembly line.

The last chapter presents a designed application where a light weight robot and a smart camera are used to assist a human working at a quality gate. The chapter includes also photos taken with a smart camera to show that the application could be implemented. Simulations done in Delmia ensure that the chosen robot is suitable for the application and the layout for the application is reliable.

2 QUALITY INSPECTION APPLICATIONS IN MANUFACTURING INDUSTRY

Quality inspection or visual inspection covers a wide variety of tasks and most of them can be automated successfully. An inspection task means a task in which a small number of features are checked and a procedure used to make the required evaluation from those features. (Soloman 1994) Using machine vision technology can provide competitive advantage by improving productivity and quality management. (Malamas et al. 2003) This chapter focuses on inspection task performed both by humans and machines. Inspection is usually performed by an operator or by AOI (automated optical inspection) and it can be used at various stages in the manufacturing process. (Talbot 2003) Machine vision and human vision have both some similarities and differences. Explaining the similarities and differences is one of the objects in this chapter. The end of this chapter includes examples from manufacturing industry. The comparison brings out the strength and weaknesses of both systems. This is followed by an analysis where an ideal inspection system for manufacturing industry is discussed.

2.1 Overview on machine and human vision

In inspection human vision involves transformation, analysis, and interpretation of images. Machine vision has the same functions called image transformation, image analysis and image interpretation. The hardware of the machine vision has same features compared to human. Both of them have lenses to focus an image and a “retina” which produces a visual signal interpreted as an image elsewhere. The performance has also some similarities as both work well where the lighting is good. Both can also be confused by shadows, glare and cryptic color patterns. However, the list of differences is longer than the similarities. A human retina consist of several millions receptors sending signals continuously. Current video cameras collect a massive amount of visual information per second. The flow of data creates a problem where the incoming data has to be reduced to be able to analyze it with computers. Machine vision is usually used to detect, identify and locate objects ignoring many of the other visual functions. (Soloman 1994)

The machine vision can perform the set of restricted functions very well allowing them to locate and measure objects better than a human eye. But which tasks are easy for machine vision system and which are hard? The answer is not that simple and the following list explains what can make something hard or problematic for machine vision.

List of contributing factors affecting complexity of the problem (Soloman 1994):

- Objects with varying details
- Lighting variations including reflections, shadows and fluctuation in brightness
- Similar unimportant features close to the important feature

Widely varying objects can be problematic for machine vision. For example stamped or milled products can be easy to inspect whereas molded or sculpted items may be harder to check. Machine vision is also very sensitive for changes in lighting. Even the natural sun light coming from a factory window can change the result of the inspection. Features which are not important but have similar features and shapes can lead to failed inspection result. (Soloman 1994)

Manual inspection and AOI have two key differences between them: the first can be called as “inspector syndrome” and the second data logging. “Inspector syndrome” means the situation where the operator becomes fatigued and de-sensitive after checking multiple times the same feature. During the work shift this leads to missed faults at some point. AOI doesn’t have this problem as it is untiring inspector. The second difference is in the data logging. The data is often logged by hand in manual inspection meaning that the operator has to accurately record every fault description and location. This will lead to a high probability of an error on the long run. (Talbot 2003)

These two differences are important when it comes to an SPC (statistical process control) tool. SPC tool can only be considered effective if the data collection is complete. At best it can provide valuable data about faults and help to identify the causes to avoid faults in the future. (Talbot 2003) In conclusion the manual inspection includes too many opportunities for faults to be missed to work as a reliable inspection method for SPC tool. When it comes to AIO the method is not also error free. Most AOI systems have problems in identifying all faults without giving a high number of false alarms. Achieving a system free of false alarms might require a long set-up time. (Talbot 2003)As a result it’s case sensitive whether AOI is suitable for collecting data for SPC. Simple AOI systems could be considered as a reliable inspection system and kept suitable method for SPC data collection.

AOI systems can fall into different categories depending on the inspection method or the tool they are using. Three of the categories are morphological reference, design rule reference and comparison reference. Morphological fault detection is commonly known as feature recognition where pre-defined list of features and shapes are analyzed. Each shape and feature is given a classification and position on the image. Those features and shapes are measured and compared to the master feature list which can be used as a reference. The data can be either from CAM data or from reference image. Design rules are usually used in conjunction with feature recognition methods.

Design rules usually consist of a series of design rule which a manufactured product must fulfill. For example inspecting certain features the features all must be of a certain width or at certain angle, and so on. If they do not meet these requirements a fault is signaled. Comparison logic is maybe the easiest to understand. It uses a thought model or an electronic image gained from a data source and compares it with the image taken from the product. The system can look for any differences in the picture and features which are out of tolerances can be signaled as a fault. The algorithm is quite sensitive and it can easily generate a large number of false alarms or missed faults. Sometimes users who use comparison logic might end up with a system with a combination of a few false alarms and the risk of undetected faults. (Talbot 2003) The technique is simple although it's quite limited. If the difference is really small a fault may be missed. Varying products may also cause false alarms. The variations in lighting can also make the technique unreliable as the technique is very sensitive for changes.

2.2 Inspection for integrated quality control

Inspection systems will have more significant role in future as they can be integrated with quality control tools and other applications. Inspection systems do not only inspect quality but generate information on the shop floor that can be passed to other process / quality control systems such as statistical process control (SPC). There are several factors that favor automatic inspection methods over manual inspection. Firstly products are becoming more complex as the technologies advance. (Zhang 1996) Some products like printed circuit board pose too great difficulties and challenge to manual inspection making it almost impossible. Secondly manual inspection is slower than automatic inspection. (Malamas et al. 2003) Manufacturing processes tend to have high production speed these days and manual inspection can't always fulfill these requirements. Thirdly the labor cost has become an issue in manufacturing industry as the manufacturing costs are tried to keep as low as possible. That drives companies to change from labor-intensive manual inspection to automatic inspection technologies and systems. (Zhang 1996)

Traditionally automatic inspection systems only detect defects and reject faulty products. Inspection systems are used either to automatically give inspection results to a machine or to provide infromation to a human operator who makes decisions based on the inspection results. These days intelligent inspection systems are able to classify defects and render probable causes of the defects. Through integration this information can help in manufacturing process diagnosis, control and optimization. The primary objective of the system integration is to achieve a higher level of information sharing and support of other systems. (Zhang 1996)

The information flow shouldn't be one way but two way. The inspection operations require support from design, quality control, production management and assembly. Information may be obtained, for example, from computer-aided design (CAD) or computer-aided manufacturing (CAM) systems. CAD or any other technical instructions contain specifications of all the expected features and complete model for inspection. CAD data reperents the original product specifications and are concidered to be defect-free in nature. Using defect-free data is much safer and more reliable than using “known good product” approach. Provided offline information helps also to reduce the set up time of the inspection system as the data is available in advance. (Zhang 1996) The information from quality control and production management can guide the inspection process which features should be checked. Notice of defects from quality control should guide inspection process to check most frequent defects while production management can inform inspection process about changes affecting inspection.

2.3 Industrial vision systems

Industrial vision systems are not capable of handling all tasks in every application fields. This has been stated earlier in this chapter. This part explains what should be taken into account when designing a machine vision system for industrial application and how the inspection process works. In classical industrial vision system images are usually acquired by one or more cameras. The positions of the cameras are usually fixed and automation systems are designed to inspect only known objects at fixed positions. The inspection scene is illuminated appropriately and features are known in advance. (Malamas et al. 2003)

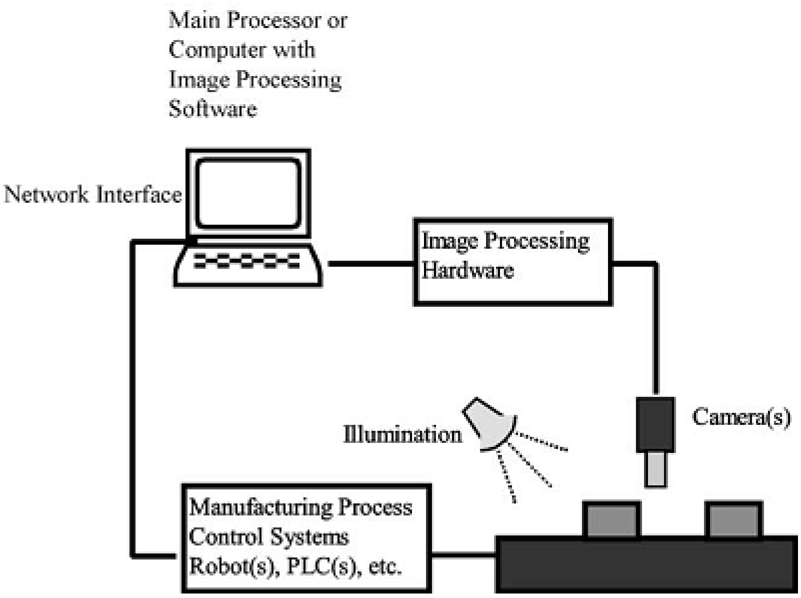


Figure 1: A typical industrial vision system (Malamas et al. 2003)

Figure 1 shows a classical industrial vision system. The Figure presents a PC-based vision system. The system could also consist of one intelligent sensor or smart camera that processes the image within the camera and communicates directly with the control system, robot or PLC. This kind of system can be used to control a manufacturing process (e.g. for guiding robot), propagate to other external device for further processing (e.g. classification) or characterize defects.

An industrial machine vision system has several attributes which are important for every application. Such attributes for inspection system are flexibility, efficiency in performance, speed, cost, reliability and robustness. It is case sensitive which attributes are important in each case. Defining required outputs and the available inputs is important when it comes to the system design. A typical industrial inspection consists of following sequence of steps:

1. Image acquisition.
2. Image processing
3. Feature extraction
4. Decision-making

In image acquisition cameras are used to capture the required information for inspection. Once the image is acquired it can be processed to remove background noise or unwanted reflections. (Malamas et al. 2003) Image processing can also be used to highlight some features in the image. Image processing has its limits and it should not be used to fix poor illumination. In feature extraction a set of known features are searched in the image. Features such and size, position, contour measurement via edge detections as well as texture measurements on regions can be measured. Modern machine vision programs have numerous tools to detect different features. The measurement results are then used in decision-making as the description of the input image.

When it comes to quality inspection most industrial vision systems fall into one of the following types of inspection:

1. Inspection of dimensional quality,
2. Inspection of surface quality,
3. Inspection of correct assembling (structural quality) and
4. Inspection of accurate or correct operation (operational quality).

The above categorization is one way to classify different kind of machine vision systems and the categories are further explained in detail in table 1. (Malamas et al. 2003) The 1 table shows that machine vision can be used for different kind of quality inspection tasks and it is not limited to one category.

Table 1: Potential features of inspected products (Malamas et al. 2003)

Dimensional	Dimensions, shape, positioning, orientation, alignment, roundness, corners	
Structural	Assembly	(Holes, slots, rivets, screws, clamps)
	Foreign objects	(Dust, bur, swarm)
Surface	Pits, scratches, cracks, wear, finish, roughness, texture, seams-folds-laps, continuity	
Operational	Incompatibility of operation to standards and specifications	

Industrial vision applications can also be classified based on degree of freedoms (DoF). These most common DoFs in industrial world are shape, geometrical dimensions, intensity, texture and pose. The DoFs of objects are related to their characteristics which can be used as a measure of the flexibility of the vision system. DoFs should be taken into account in the design phase. Designing a system with high DoFs allows it to be expanded later. Low DoFs reduces the options how the vision system can be modified and what can it be used for. (Malamas et al. 2003)

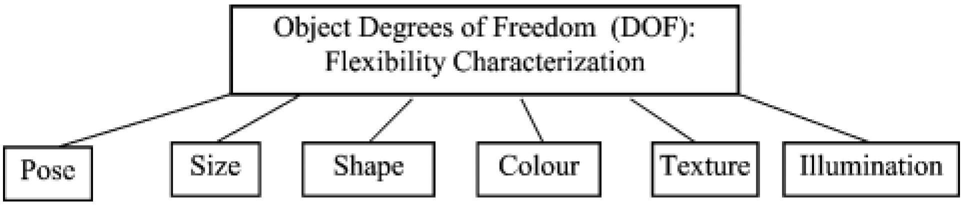


Figure 2: Major DoFs in industrial vision systems. (Malamas et al. 2003)

The classification presented above shows that decisions made in the design of inspection system. One must take into account all DoFs which is usually a trade-off between flexibility, complexity and cost. This point of view is not obvious in other classifications. All of the DoFs are not equally important as a few of them can be considered more important than the others. (Malamas et al. 2003) For example illumination and pose can be considered quite important DoFs. A well designed system can be ruined with a poor illumination. Size and pose can be both modified at any point with certain limits if the system has more than one camera or the camera is not fixed but located on the end effector. (Soloman 1994)

2.4 Application examples

Visual inspection systems can be categorized in different ways as told in Chapter 2.3. This part presents a few application examples about automatic inspection systems. Strength and weaknesses of each system are considered and compared among each other's. In addition the requirements for the inspection environment are analyzed in each case.

2.4.1 Robot-mounted 3D optical scanning devices

The following application is an example where a laser probe was mounted on industrial robot's end effector. The application is an experimental version but is a perfect example of an industrial inspection system. The system was designed for small batch sizes and high number of product variants for the needs of automotive industry.

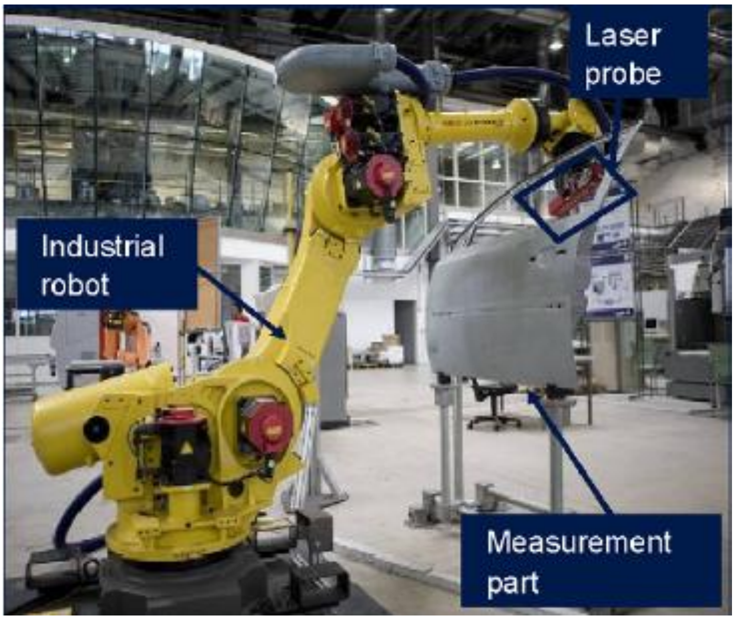
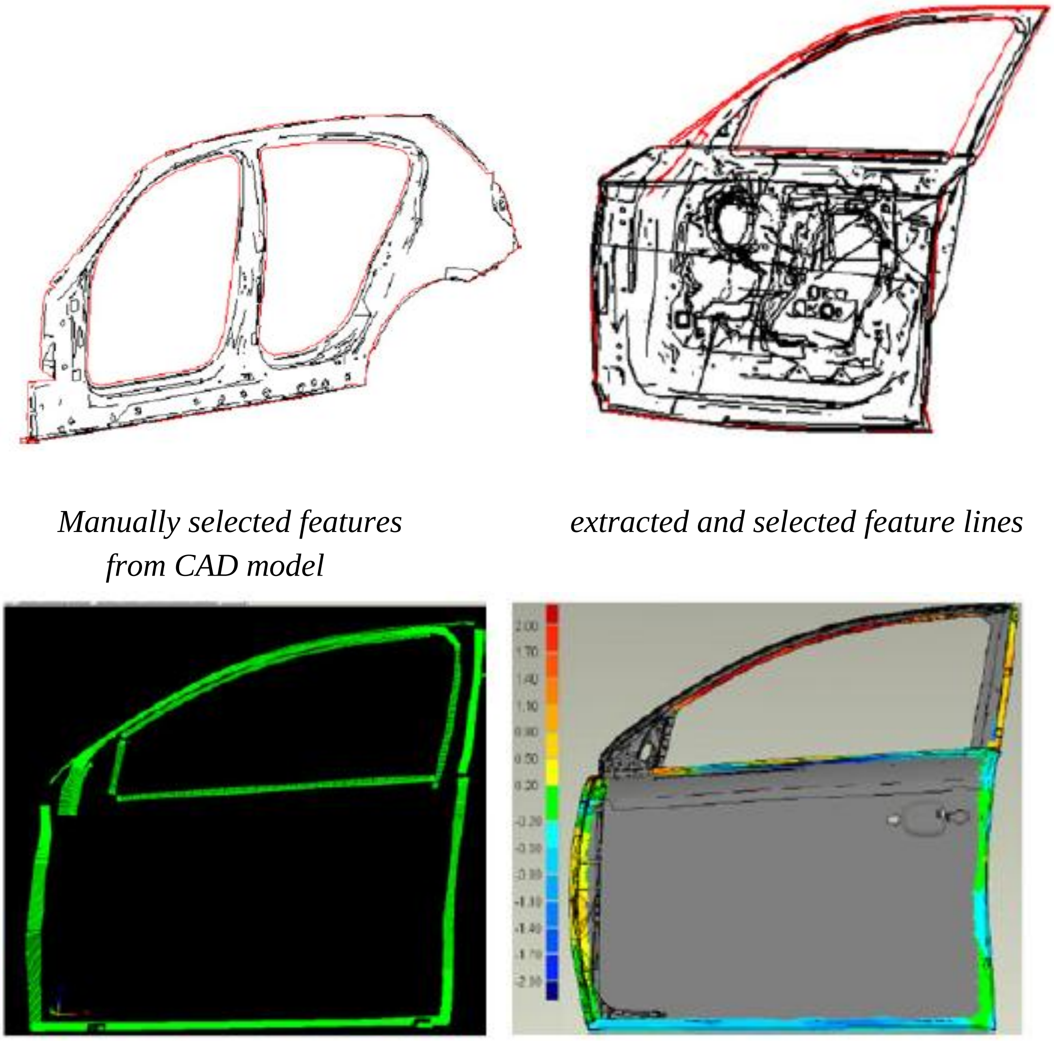


Figure 3: Automatic inspection system with optical scanning device (Reinhart & Tekouo 2009)

The system was developed to identify and recover from quality troubles as early as possible. This means inspecting all parts before the assembly to assure that all parts meet their specifications. Mass production has increased the number of parts and as a result programming of a robot would be time consuming for all parts. The inspection system was planned to generate robot's path for each part automatically from CAD models. Generating the path manually could be cumbersome as the laser trajectories have to satisfy several constraints such as view angle, field of view, depth of view and self-obstruction. In addition optimized scanning paths reduce overall scanning time providing the best cycle time. (Reinhart & Tekouo 2009)

The system was developed to allow an operator to modify and select features from CAD-models which of them should be inspected.



Manually selected features from CAD model

extracted and selected feature lines

measurement data

shape error map

Figure 4: Selected features and scanning results (Reinhart & Tekouo 2009)

This system has several strengths such as wide variety of products that can be inspected. Only the size and the shape of the product can set some limits to the inspection. A six-axis industrial robot allows adjustable field of view, depth of view and view angle. Using an industrial robot makes the inspection system more flexible. A laser probe is suitable for measuring dimensions especially in 3D but it won’t be able to inspect textures, colors or any other small defects in the surface. A laser probe doesn’t need a special illumination like other classical machine vision systems with CCD cameras.

2.4.2 Automated inspection of axial piston motors

The second example is an automated inspection in a semi-automated assembly process. The parts being inspected in this case are the pump case, shaft, cylinder block, valve plate and valve cover. For manual inspection process the precise position of the parts is not relevant as the operator can pick up the parts and turn them around. In this case the automated inspection system has multiple cameras and parts being inspected are always presented in the same position. The requirements for the lighting are the same. The lighting has to be fixed and remain same in every inspection. Even small changes in the lighting can have an impact on inspection result.

In the following Figure all components are placed onto one large fixture design in order for multiple cameras to view all components in one inspection position. The system consists of total 6 machine vision cameras which are connected to a central PC unit running the machine vision software.

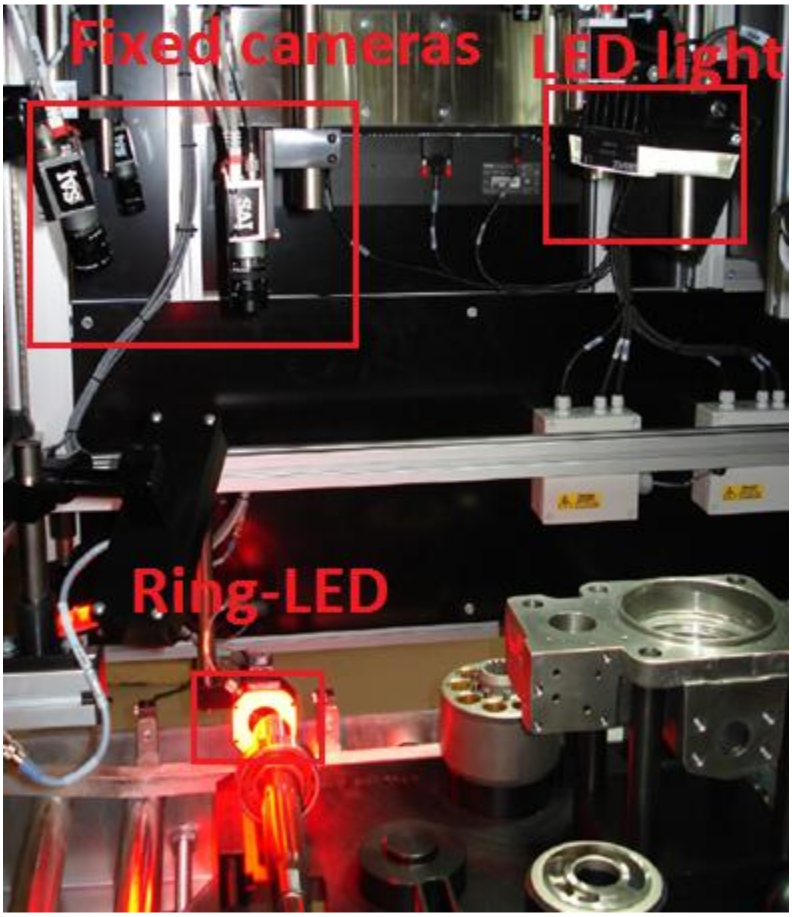


Figure 5: Inspection of axial piston motors. (Industrial Vision Systems Ltd.)

The lighting includes a combination of high intensity white LED area light units with built in polarizers combined with red LED ring lights. The inspection scene was shielded from ambient lighting to prevent it affecting the inspecting results. (Industrial Vision Systems Ltd.)

The application has quite many requirements for the inspection environment. As the cameras are fixed the fixture has to stop exactly at the same position every time. If the system was reconfigured to check other products one would have to consider several things as camera angles and lighting. As the system has several illumination sources changing one light source could affect lighting of other parts too. Due to shielding the system can be considered really stable and free from external disturbances. Using fixed cameras and fixtures make also the system stable and reliable although they reduce the flexibility of the system.

2.5 Considerations

It is always case sensitive what kind of a solution is ideal for each application. However the system can be designed in a way that it presents an ideal design for the inspection task. Earlier in this chapter DoFs was discussed. The DoF is always a trade-off between flexibility, complexity and cost. An ideal system would have high flexibility while keeping it simple and cheap. The flexibility of the system can be increased by having multiple cameras or installing the camera on a robot. At the same time they increase the complexity and the cost of the system. At some point an industrial robot becomes cheaper than multiple cameras. In addition a robot offers adjustable view points and field of view.

In ideal quality inspection most of the tasks are checked by a machine. Data logging and information reports are completed automatically to avoid any errors. The ideal information flow works in two ways in real-time. An inspection system generates a huge amount of information that could be used to improve manufacturing process. Manual inspection is also important where human judgment and problem solving are required. Sometimes the ideal application might require be the combination of manual and automatic inspection. Web browser technology and GUIs should be utilized to allow users to monitor inspection process easily and interact effortlessly with the process if needed.

3 LIGHT WEIGHT ROBOTS

Light weight robots (LWR) are a new generation of torque-controlled robots developed for application areas different from the classical industrial robots or where the use of industrial robot is not applicable. Such areas are assembly processes where the position estimation for the mating parts and/or the positioning accuracy of the robot is significantly below the assembly tolerance, robot works in immediate vicinity of humans and mobile service robots with relatively high uncertain information about the surrounding objects. LWR have features which separate them from classical robots. Features such as load-to-weight ratio of 1:1-1:3, torque sensing in the joints, active vibration damping, sensitive collision detection, compliant control on joint and Cartesian level allow light weight robots to operate in unstructured environments and interact with humans. (Albu-Schäffer et al. 2007) This chapter provides details about the construction of the light weight robot. To fully understand the principle of LWR this work presents shortly control methods used to control LWR. These details should provide enough information to understand and explain why physical human-robot interaction is safe using LWR. In the end of this chapter a comparison between LWR and classical industrial summarizes how they differ from each other.

3.1 Structure of the light weight robot

High speed, high positioning accuracy (repeatability and absolute accuracy) and durability are typical properties to a classical industrial robot. These requirements often require high stiffness resulting in large robot mass relative to its payload. Industrial robots typically have a load-to-weight ratio of 1:10 or lower whereas LWR’s ratio is approximately 1:1. (Hirzinger et al. 2002) Light-weight robots are designed to interact with a human that sets some constraints to the construction of LWR. To enable mobility and to minimize the injury risk a low robot mass is required. The mass reduction makes LWR also less rigid causing vibration. Control methods used to overcome this problem is covered later in Chapter 3.1.2. From the electronic design point of view requirements set for LWR are high number of sensors, such as joint torque sensors, redundant position sensing and wrist force-torque sensing. In light weight robots motor and sensor electronics are integrated to reduce the number of wires in the manipulator. Integration is only possible via fast and deterministic bus communication between joints to allow implementation of control algorithms on a central computer. (Albu-Schäffer et al. 2007)

Light weight robots have different kind of structures depending on the manufacturer. Different kind of light weight robots are presented in the Table 2. The first two robots are classical industrial light weight robots (requires external safety equipment) while the rest of them represent collaborative robots. Compliance in this case means that a robot is safe and it can work in the shared working area with human.

Table 2: Technical specifications of some LWR arms

LWR type	DoF	Range (mm)	Weight (kg)	Pay-load (kg)	Repeatabil-ity (mm)	Tip speed (m/s)	Compli-ance	Reference
IRB 120	6	580	25	3	+/- 0.01 mm		no	ABB
KR 6 R700	6	706	50	6	+/- 0.03 mm	-	no	KUKA
SDA10	15	985	220	10	+/- 0.1 mm	-	yes	MOTOMAN
Baxter	14	1041	74	2.2+2.2	-	0.6	yes	Rethink Robotics
LBR iiwa 7R820	7	820	23.9	7	+/- 0.1 mm	-	yes	KUKA
LBR iiwa 7R800	7	800	29.9	14	+/- 0.1 mm	-	yes	KUKA
UR 5	6	850	18.4	5	+/- 0.1 mm	1.0	yes	Universal Robots
UR 10	6	1300	28.9	10	+/- 0.1 mm	1.0	yes	Universal Robots

Figure 6: Examples of light weight industrial robots

Classical industrial robots also have different kind of joints compared to light weight robots. Each of the joint units in classical industrial robot is unique whereas collaborative robots have used modular joint units composing of a few basic components. The modularity concept has been supported by kinematic-dynamic analysis and design software based on concurrent engineering. In future any type of a robot could be assembled by using the link component library. (Gombert et al. 1994; Hirzinger et al. 2002) Using modular components has a number of advantages such as rotation symmetric components, few single parts, simply exchangeable motor assembly and closed arm structure. (Hirzinger et al. 2002)

3.1.1 Kinematics

Kinematics of a robot defines the manipulability of the robot. Current manufacturers offer light weight robots which have six or more DoFs up to fifteen DoFs. Kinematics of the light-weight robots depends on its application area and usually the characteristics of a robot explain the kinematic configuration. For example DLR's robot has seven DoFs whereas Universal robot's UR10 has only six. UR10 resembles classical articulated six degree-of-freedom robot while DLR's robot was planned to work like a human arm. To execute an elbow motion while keeping the pose of the hand same seven joints are required. (Bischoff et al. 2010) Manipulators with dual-arm concept like Motoman's SDA10 usually have 14-15 DoFs as they are built to have kinematic redundancy similar to human arms.

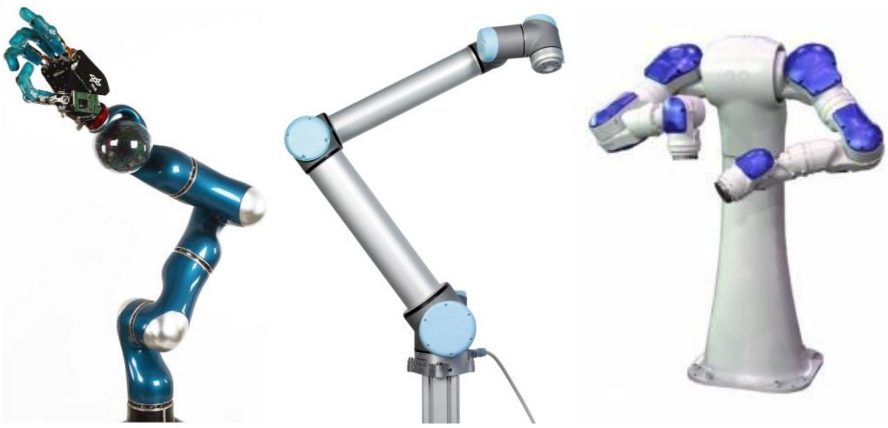


Figure 7: The DLR LWR arm and hand (Albu-Schäffer et al. 2007) on the left and Universal Robots' UR10 (Universal Robots) in the middle and Motorman's SDA10 on the right.

As there has been lots of research on kinematics of light weight robot new results has been discovered that can allow higher mobility than classical industrial robots. The kinematic-dynamic simulations revealed that a ball-shaped two axis wrist joint, imitating the human wrist, showed much higher mobility. Robots most important joints are the wrist joints as the manipulability of the robot depends on them. When the distance between wrist-pitch axis to tool-center-point is short, the robot doesn't have to execute big movements while changing the orientation of the wrist. (Hirzinger et al. 2002) In addition simulation model results suggested that the distances between joints 2-4 should be equal to achieve optimal joint configuration. The joints should also be perpendicular joints (Hirzinger et al. 2001a). The Figure 7 presents different configuration models for a light weight robot.

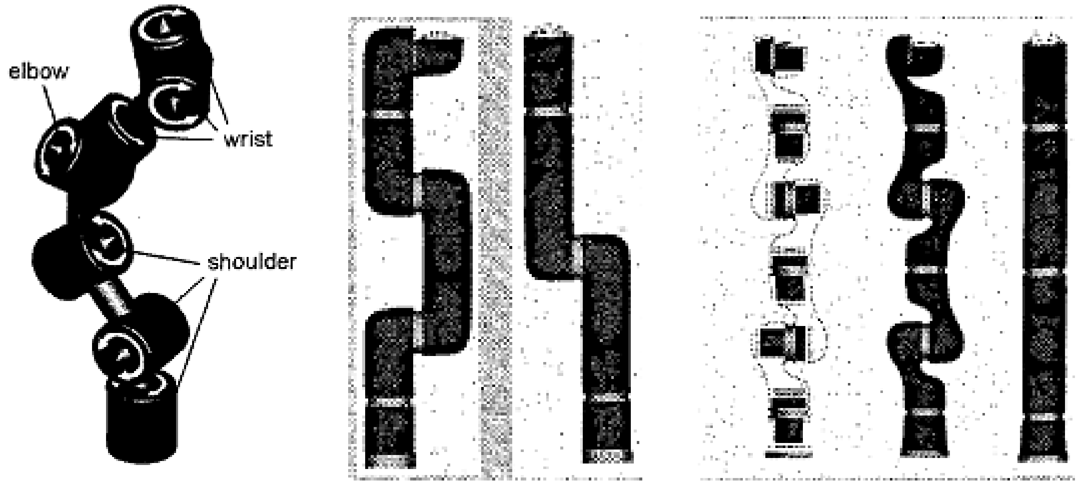


Figure 8: Robot kinematics of the DLR LWR (Hirzinger et al. 2001a) on the left, asymmetrical in the middle and symmetrical robot configuration on the right. (Hirzinger et al. 2002)

For some applications it’s important that the robot can be folded to save space. Asymmetrical configuration allows the robot to be easily folded. This is an advantage when the robot has to be transported or moved.

3.1.2 Joint units

As joint units can be modular the joint units should be identical or there should be only a few modifications or units. For example each joint of the DLR’s LWR has ability to sense torques which is important for the safety and control issues. Joint torques acting on the links can be measured with torque sensors mounted on the flex spline that is part of the Harmonic Drive. (Albu-Schäffer et al. 2007) Harmonic Drive gearing is known for zero backlash, high torque, compact size, and excellent positional accuracy which make it an ideal choice for light-weight robots. An additional bearing is used to decouple disturbing forces and torques in the joint. The data must transmit very fast between the joints and central computer to enable real-time control. In light weight robots joins can be serially connected with the central computer via an optical bus system. DLR’s joints are controlled individually on a signal processor at 3 kHz rate in each joint. The robot dynamics and the Cartesian control are typically computed in a 1 kHz cycle on a central computer. (Albu-Schäffer et al. 2007) Serially connected joints also reduce amount of cables and space required for housing.

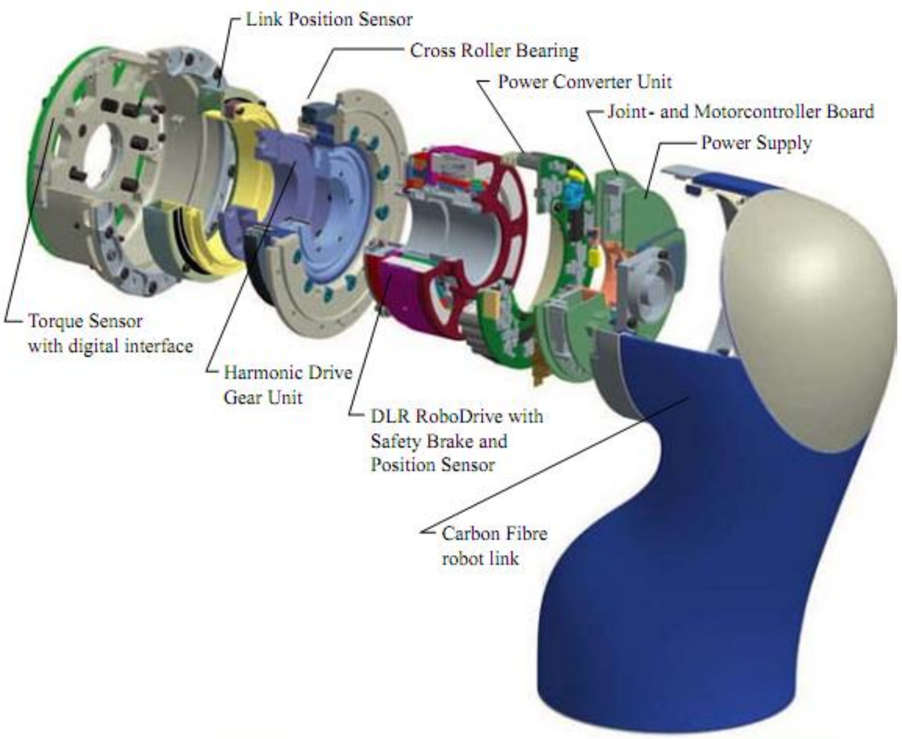


Figure 9: The joint design of the DLR's LWR (Albu-Schäffer et al. 2007)

DLR has used carbon fiber in its robot links. Universal Robots have used aluminum and acrylonitrile butadiene styrene (ABS) plastic in its robot links. The main goal on both cases is to reduce mass. Using aluminum can save up to 40 % weight. In addition of torque sensors each link has also a link position sensor and electromagnetic brake. (Hirzinger et al. 2001b)

3.2 Control methods

Typical rigid manipulators have a stiff connection between the motor and the link. This results in high output impedance dominated by the sum of the link and the reflected rotor inertia. Rotor inertia is often high due to the high gear ratio that makes the robot unsafe during collisions. (Laffranchi et al. 2009) To overcome this problem light-weight robots require more sophisticated control methods than classical industrial robots. As mentioned before, torque sensing and feedback control are essential to achieve accurate motion for flexible manipulator as well as monitored control of forces caused by unstructured environments. Light-weight robots are likely to collide or to be in contact with its surrounding environment for what they are designed for. The collision detection can't be carried out by observing forces in the robot tool tip because the collision can occur in any part of the robot arm. Torque sensing solves this problem with collocated sensors placed close to the joints. From control point of view this enables robust and passivity-based control approach. (Albu-Schäffer et al. 2007) The control method doesn't only allow human presence but also manipulation of objects and contacted environment which are not precisely known.

3.2.1 Joint level control

Joint level control is implemented in each joint locally with a full state feedback controller using motor position, velocity (θ,θ) as well as the joint torque and its derivative (τ, τ) (Albu-Schäffer et al. 2007). By using appropriate feedback gains the controller can be used to establish a mass-damper-spring relationship between the Cartesian position Δx and the Cartesian force f:

$$f = M\Delta x + D_k\Delta x + K_k\Delta x, \qquad [1] \qquad \text{(Albu-Schäffer \& Hirzinger 2002)}$$

where M, D_k and K_k are positive definite matrices representing the virtual inertia, damping and stiffness of the system. Gains depend on what kind of motion the robot has to perform. When the torque is controlled the controller has high torque and torque derivative gains while the position control is achieved by using high position and velocity gains. The robot dynamics affect the commanded torque for the controller. The robot can then work in “zero gravity mode” in which the motors compensate the robot’s own weight. The mode can be used to avoid injuries in collisions and also in teach mode when an operator is teaching trajectories. (Albu-Schäffer et al. 2007)

The feedback terms of a controller can be linked directly to physical terms. The torque feedback corresponds with the inertia of the motors and the joint friction. The motor position feedback corresponds with a physical spring where velocity feedback produces energy dissipation. (Albu-Schäffer et al. 2007) The Figure 9 presents a structure of joint level controller.

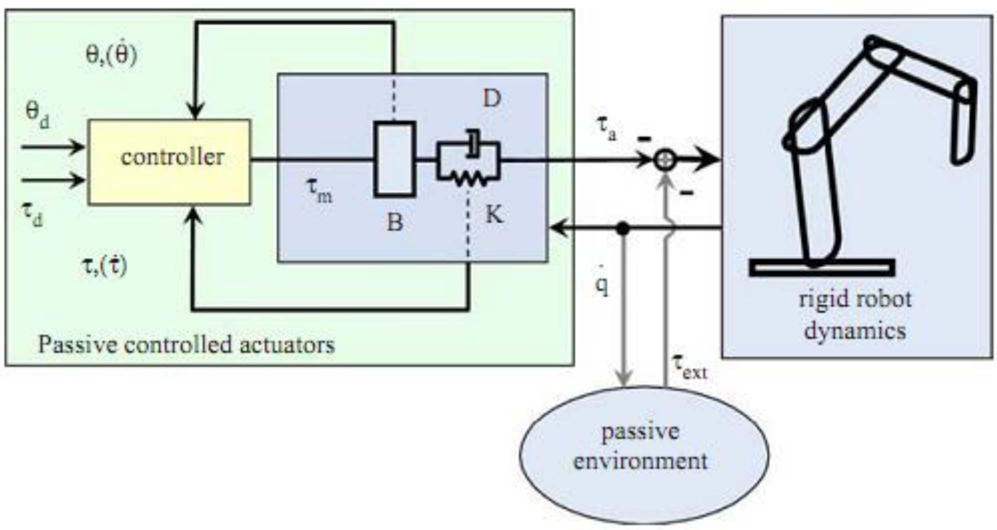


Figure 10: Structure of joint level controller (Albu-Schäffer et al. 2007)

To demonstrate the need for a state feedback controller the Figure 10 shows a comparison between state feedback controller and a PD-controller. Both controllers use torque signal for signal damping.

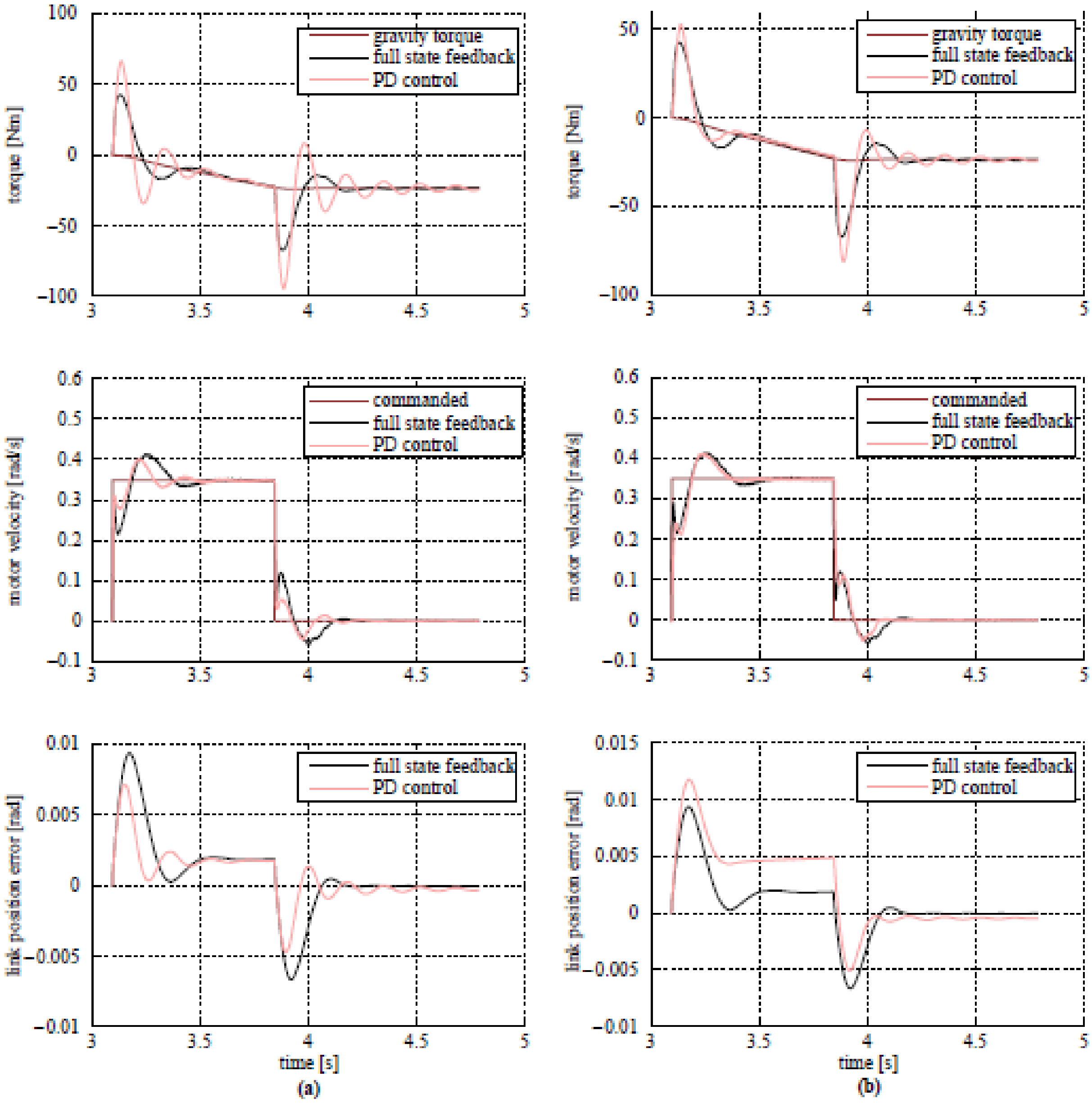


Figure 11: PD-controller versus state feedback controller. On the left (a) the gains are identical and on the right (b) the gains of the PD controller are reduced. (Albu-Schäffer et al. 2007)

With identical gains (a) the state feedback controller is well damped but a little bit slower while the PD-controller exhibits strong oscillation. In the Figure 10 (b) the position feedback for the PD-controller has been decreased in order to achieve the same link side stiffness as for the state feedback controller. With decreased gain the response time for both controllers are similar, but the position error of the PD-controller is considerably larger and the oscillation still exists at the end of the trajectory on the torque signal. (Albu-Schäffer et al. 2007)

Cartesian compliant motion can be realized in different ways depending on the structure of the joint control. Three different strategies for implementing it are admittance control, impedance control and Cartesian stiffness control. The chapter 3.2.2 shortly discusses the main features of the controllers and how they differ from classical industrial robot controllers.

3.2.2 Cartesian impedance control

Light weight robots were designed to work in applications where they are mainly in contact with the environment. That leads to a situation where it is sometimes useful to control the forces rather than the positions in some Cartesian directions. Cartesian impedance controller allows a smooth transition between force and position control when the relation between them is specified. (Albu-Schäffer et al. 2007) The Figure 11 presents the structure of Cartesian impedance controller.

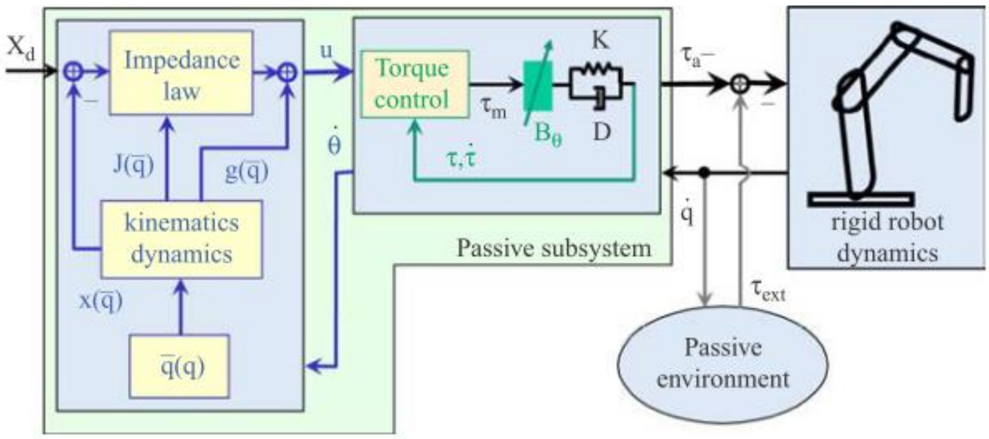


Figure 12: Structure of Cartesian impedance controller (Albu-Schäffer et al. 2007)

The Cartesian impedance controller works as a position controller or a torque controller depending on the parameters (gains). The parameters are computed in the central robot controller in every Cartesian cycle. The cycle also includes determination of the robot dynamics, the kinematics and the inverse kinematics (Albu-Schäffer & Hirzinger 2002). The controller structure differs from a classical PD-controller as the motor inertia and the joint stiffness are included in the same passive block. The state feedback controller consists of inner and outer loop in this case. The fast inner loop controls joint torques and it receives its set point values from an outer impedance controller. The structure of the controller enables an effective damping of the joint oscillation. (Ott et al. 2008)

The impedance controller suits well for low stiffness and damping. The controller has only problems with high Cartesian stiffness. The Cartesian stiffness problem can be solved with an impedance controller enhanced by local stiffness control. (Albu-Schäffer & Hirzinger 2002)

Cartesian compliant motion consists of three different strategies which are presented in the Figure 12.

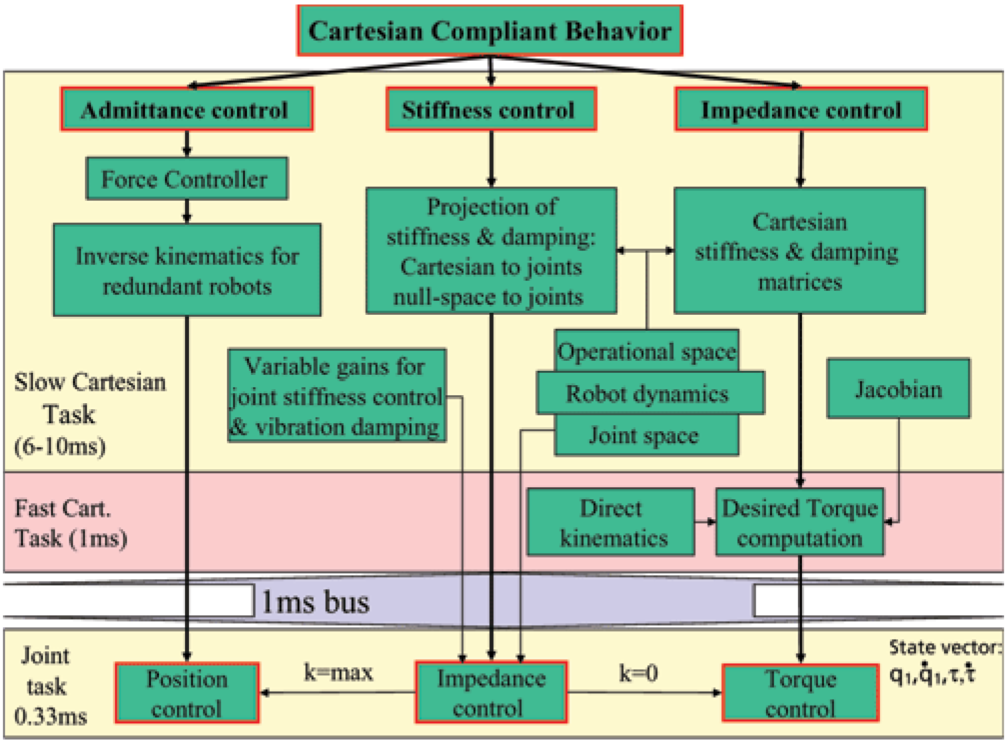


Figure 13: Controller architecture (DLR - Institut für Robotik und Mechatronik)

Admittance control accesses the joint position interface through the inverse kinematics while the impedance control is based on the joint torque interface. The Cartesian stiffness control accesses the joint impedance controller.

The impedance controller enhanced by local stiffness control is suitable for applications where the robot is in contact with unknown environment. In comparison to admittance control it has lower geometric accuracy but better bandwidth and impedance range. (Hirzinger et al. 2002) Classical industrial robots use admittance control that is the most commonly used one, since they have only a position interface. Stiffness and impedance control is only possible if the robot has torque sensors or joint impedance interface in each joint.(Albu-Schäffer & Hirzinger 2002)

3.3 Safety and physical human-robot collaboration

Safety functions of industrial robot controller and types of collaborative operations are listed in ISO 10218-1. To meet required safety criteria a collaborative robot must meet one of following criteria: safety-rated monitored stop, hand guiding, speed and separation monitoring or power and force limiting. The criteria range from discrete safety (no human-robot collaboration (HRC)) to full HRC. Safety standards have been harmonized and identified by ISO 10218:2011 and ANSI/RIA R15.06-2012. (Anandan) The old standard ANSI/RIA R15.06-1999 can be used until the end of 2014.

Collaborative operation is defined as a state in which robot is purposely designed to work in direct cooperation with a human within a defined workspace. Different types of collaborative operations are presented in the Figure 13.

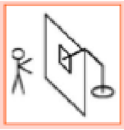
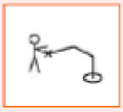
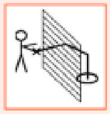
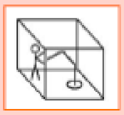
ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	Pictogram (ISO 10218-2)
5.10.2	Safety-rated monitored stop (Example: manual loading-station)	No robot motion when operator is in collaborative work space	
5.10.3	Hand guiding (Example: operation as assist device)	Robot motion only through direct input of operator	 
5.10.4	Speed and separation monitoring (Example: replenishing parts containers)	Robot motion only when separation distance above minimum separation distance	 
5.10.5	Power and force limiting by inherent design or control (Example: *ABB Dual-Arm Concept Robot* collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

Figure 14: Types of collaborative operation according to ISO 10218-1 (Matthias 2014)

Safety-rated monitored stop is performed with external sensors which mean that a robot has to stop before a human can enter the work space. In hand guiding a robot can perform motion only through direct input of operator and the safety is assured with a safety switch. Speed and separation monitoring is also performed with external sensors (for example laser scanners or machine vision). The robot can then detect a human approaching robot's workspace and reduce speed or stop if a human comes too close. The last risk reduction type is power and force limiting by inherent design or control. Power and force limiting is the method used in light weight robots that allow building collaborative industrial robots and full HRC.

The allowed speed, separation distance, torques, operator controls and main risk reduction method varies according to the type of collaborative operation. These attributes are listed in the Figure 14.

	Speed	Separation distance	Torques	Operator controls	Main risk reduction
Safety-rated monitored stop	Zero while operator in CWS*	Small or zero	Gravity + load compensation only	None while operator in CWS*	No motion in presence of operator
Hand guiding	Safety-rated monitored speed (PL d)	Small or zero	As by direct operator input	E-stop; Enabling device; Motion input	Motion only by direct operator input
Speed and separation monitoring	Safety-rated monitored speed (PL d)	Safety-rated monitored distance (PL d)	As required to execute application and maintain min. separ. distance	None while operator in CWS*	Contact between robot and operator prevented
Power and force limiting	Max. determined by RA⁺ to limit impact forces	Small or zero	Max. determined by RA⁺ to limit static forces	As required for application	By design or control, robot cannot impart excessive force

Figure 15: Types of collaborative operations and their attributes. (Matthias 2014) (CWS = Collaborative Work Space, RA = Risk Assessment)

This work concentrates on the last option force and power limiting because it can be included within light-weight robots without any external equipment. The following Chapter 3.3.1 explains more about force and power limitations.

3.3.1 Force and power limitations

The ISO-10218 states that that one of the following condition has to be fulfilled for allowing human-robot interaction: The TCP/flange velocity has to be ≤ 0.25m/s, the maximum dynamic power ≤ 80W or the maximum static force ≤ 150N. (Haddadin et al. 2011) Force and power limiting method is based on torque sensing. Because every joint has its own torque sensor the robot can detect collisions occurring anywhere in the robot arm. For example Universal Robots' UR10 force is controlled by high level software which stops the robot in case of an impact. This stop for limit is lower than 150N as required. In addition joint forces are controlled with low level software where the joint torques are limited and only a small deviation from the expected torque is permitted. (Universal Robots)

The robot can have multiple limitations that can improve the safety. For example Universal Robots' has 8 adjustable safety functions. The robot has general limits (force, power and speed), joint limits (joint speed, joint position), boundaries (Cartesian space and tool orientation) and safety I/O (for example emergency stop). Adjustable safety functions allow robot to work in different safety modes. For example robot can work in least restricted mode inside a CNC machine, behind fences and hard-to-reach places. This allows better performance as the movement of the robot doesn't have to be restricted. Working in normal mode usually means working within limitations and where people are aware of the robot arm and its payload. When working in unknown environment a reduced mode can be triggered. Reduced mode can also be activated when the risk of collision with the robot arm is high or the payload is heavy. If robot violates one of the limitations it stops and goes into recovery mode. In recovery mode the robot program can't be executed until the violations have been resolved. Only manual adjustments are possible in recovery mode within fixed limitations which are not adjustable by the user.

Force is considered as the maximum force that the robot TCP exerts on the environment while power is considered as the maximum mechanical work produced by the robot. Robots payload affects this value as it's considered to be part of the robot. Speed corresponds with the linear speed of the robot TCP and momentum corresponds with the momentum of the robot arm. For example Universal Robots UR 5 force can be limited between 100N and 250N, power between 80W and 1000W. The speed limit doesn't apply to whole robot arm but only to TCP. Robot arm speed can be limited by adjusting joint speed limits.

3.3.2 Collision case study

Collisions caused by robots have been studied widely. Every part of the human body can take an impact without getting injured. Things affecting in the collision are the shape of the objects, mass of the objects and velocities. Also the environment affects the results: clamped objects receive the impact in a different way.

DLR's LWR has been tested at the Crash Test Center of the German Automobile Club ADAC. In the test a crush dummy collided with a robot to find out how severe damage torque controlled robot can cause. The Head Injury Criterion (HIC) is an assessment criteria used in pedestrian impact test created by European New Car Assessment Programme (Euro NCAP). In the Figure 15 HIC result plots represent an impact of DLR's LWR on crush dummy's head up to velocity of 2 m/s. DLR LWR III weights 14kg and the mounted tool 1.4kg. (Haddadin et al. 2011)

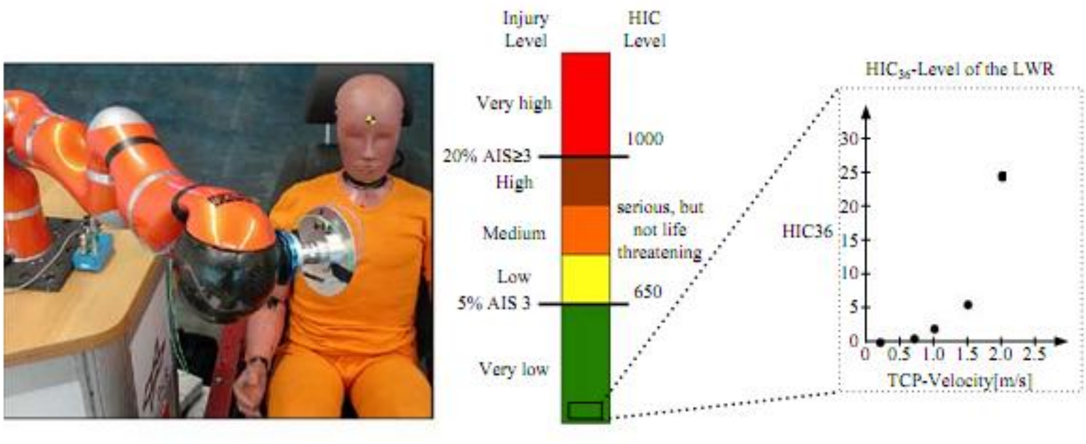


Figure 16: Injury level of the human head caused by DLR LWR III (Albu-Schäffer et al. 2007)

In the bar the result are in the lower quarter of the green bar. The HIC results under 650 are considered very low level injury risk. The value 650 corresponds to a chance of five percent to receive a serious injury. (Albu-Schäffer et al. 2007) The study shows that HIC results of DLR LWR III is very low and poses a very small threat with low speeds. (Haddadin et al. 2011) Another studies about the same subject present that the DLR LWR III could move at speed of 1 m/s without causing any fractures.

The test shows how severe threat a light-weight robot can pose. The resulted injury depends on the weight of the robot, impact velocity and power limits used. The above HIC test shows only case where the head is clamped and robot's tool is blunt. The threat of injury consists always from environment, robot and tool mass and shape. The HIC test doesn't show threat of injury caused by environment or sharp objects.

3.4 Comparison between classical industrial robots and light weight robots

This chapter included already some information about differences between classical industrial robots and collaborative light weight robots. The following part summarizes these and presents some visions about future production assistant that could be implemented with light weight robots but not with classical industrial robots.

Table 3: Comparing present and future production with robots (Bischoff et al. 2010)

"Classical" industrial robot	Future production assistant
fixed installation	flexibly relocatable (manually or on mobile robots)
periodic, repeatable tasks; seldom changes	frequent task changes; tasks seldom repeated
programmed online / offline by a robot specialist	instructed online by a process expert supported by offline methods
infrequent interaction with the worker only during programming	frequent interaction with the worker, even force / precision assistance
worker and robot separated by fences	workspace sharing with the worker
profitable only with medium to large lot sizes	profitable even with small lot sizes

Due to light weight of LWR it can be easily transported with a mobile platform or carried manually to a different location. With classical industrial robots this could not be implemented so easily due to high weight. In addition classical industrial robots usually need fixed installation to achieve desired accuracy. As LWRs can be moved easily they can adapt to changes more easily than classical industrial robots. Light weight robots ability to work in zero gravity mode allows online instruction by a process operator which allows faster online teaching. Interaction with classical industrial robots is not frequent as safety devices prevent the access to the robot cell. Interaction occurs usually when robots have to be reprogrammed or in case of an error. In most cases LWRs don´t require any external safety devices which enables co-operation between a worker and a robot. A worker can guide a robot and work together with the robot while sharing the same work space. As the LWRs can be easily reprogrammed for new products the profitable lot sizes become smaller. In addition LWR system doesn't require external safety equipment which tend to be expensive. Reducing the overall system price makes the investment profitable even for the smaller batch sizes. The Figure 16 shows the area where light weight robots are most likely to appear.

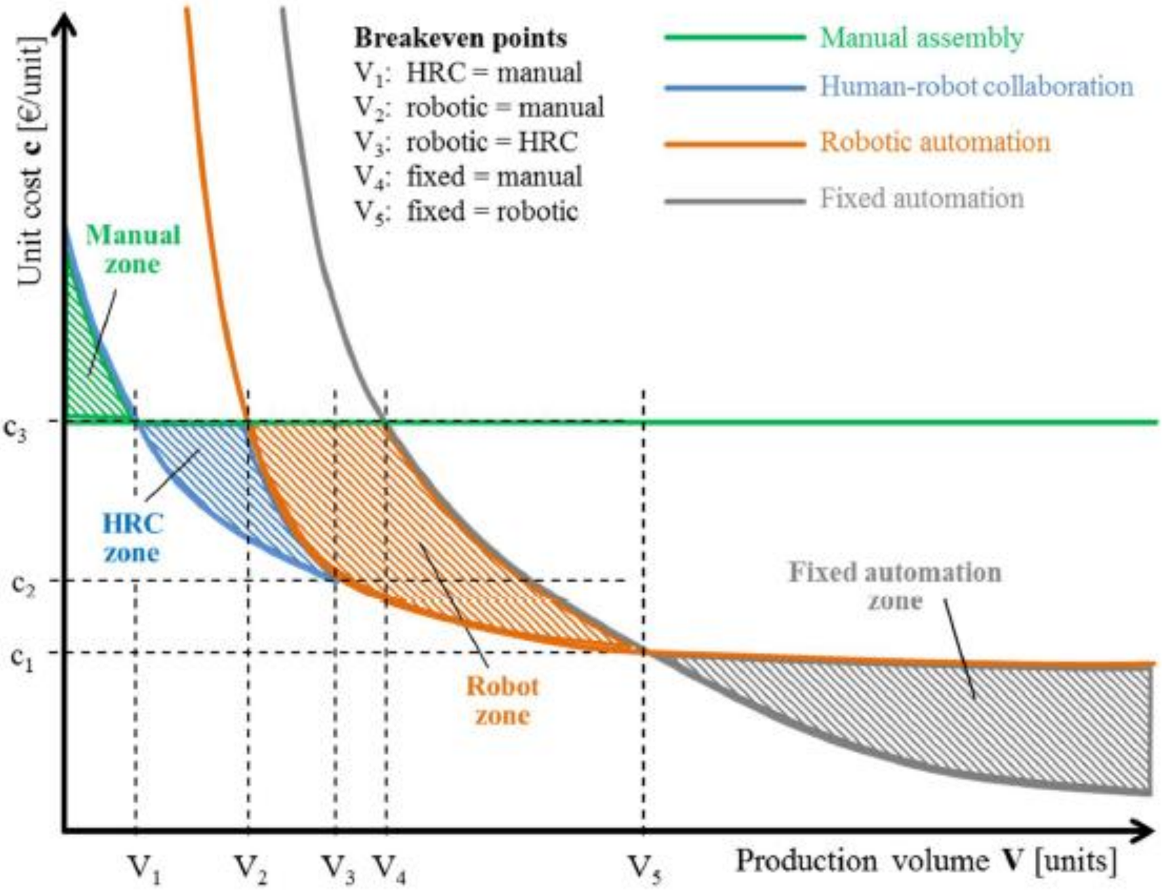


Figure 17: Productivity zones for different assembly methods. (Matthias 2014)

HRC zone can also be called as hybrid zone as the production includes both manual and robotic production. This is a new zone where the use of manual production is too expensive and robotic automation is not reasonable due to small batch sizes or the nature of production task.

Table 4: Differences between classical industrial robots and light weight robots. (Bischoff et al. 2010)

"Classical" industrial robot	**Light weight robots**
load-to-weight ratio 1:10	load-to-weight ratio 1:1 - 1:3
no torque sensing or torque sensing in one joint	torque sensing in every joint
high mass and high stiffness → great repeatability and absolute accuracy	low mass and low stiffness → requires active vibration damping
can detect collisions but not in a sensitive way	sensitive collision detection, detects collisions quickly
possible control method: admittance control	possible control methods: admittance control stiffness control impedance control
can't operate in unstructured environments and interact with humans	can operate in unstructured environments and interact with humans

Light weight robots have better load-to-weight ratio but their payload is reduced to small weights due to light weight of the robot structure. Therefore classical robots are a natural choice over light weight robots when the weight of an object is heavy. For example Universal Robots UR 10 can lift up objects up to 10 kilo. Light weight robots often have torque sensing in every joint making them more robust for assembly operations where mating parts can be hard due to varying and small tolerances or unknown orientation. The strength of the classical industrial robot is its great repeatability and absolute accuracy. High stiffness allows fast movements without losing accuracy in the process. Light weight robots require active vibration damping to overcome problems caused by low stiffness. The moving speed is also slower due to safety regulations. Light weight robots can be programmed to move faster but those applications require external safety equipment to ensure that robot doesn't move fast when a human is nearby.

AGCO Power has one application with force control. In this application an industrial robot ABB 5500 assembles a camshaft among other components into a diesel engine. The camshaft is assembled from top-down direction pushing the camshaft down. If the camshaft doesn't go into the diesel engine the robot makes a circular movement while trying to push the camshaft down. This kind application requires force control methods which classical industrial usually don't have if it haven't been added. The force control is then implemented in one joint usually located in the wrist of the robot. Light weight robots could easily do this task without investing in additional force control technology. One thing that could limit using light weight control in this application is the reach and the payload capacity of light weight robots.

3.5 Considerations

Light robots are a new generation of collaborative robots and the standards are evolving while more research is done to improve safety and performance of light weight robots. Robot manufacturers offer already a wide range of light weight robots. Some of the robots are relatively cheap and the total system price might be smaller than classical industrial robots as the safety equipment tend to increase total system cost. However the most advanced light weight robots are expensive but they can work in unstructured environment and perform complex assembly tasks that classical industrial robots can’t perform.

It is case sensitive whether the use of collaborative light weight robot is cheaper or more advantageous over classical industrial robots. Both have their advantages: classical industrial robots are rigid, fast and accurate while LWRs are compliant and they have better ability to work in unstructured environment. In future light weight robots might come more popular if lot sizes are getting smaller. So called hybrid assembly where human and robots work together are more likely to appear in applications where manual assembly is considered too expensive and lot sizes doesn’t require robotic automation. Light weight robots are designed for hybrid assembly as they can be easily moved and set ups for new assembly tasks.

4 DESIGNED INSPECTION SYSTEM

One robot and a smart camera can provide an effective way to fulfill a large scale quality inspection. This chapter presents an application where different features from different products are inspected by a smart camera and a light weight robot. The application is based on theory that has been presented earlier in Chapters two and three. The work load is divided so that repetitive and easily detected features are inspected by machine vision. The objective of this work is not to make a worker unemployed but to easy his/her work load and increase the quality by detecting the defects. Combining the strengths of human and machine vision increases the quality and the content of the work. A worker is then free from boring and repetitive work and he/she can focus on other features when most of the features are inspected automatically.

A robot can effectively move a smart camera to the desired position required to capture a good image. A diesel engine is also a relatively big product so one camera or two cameras wouldn’t be enough to cover whole product not to speak of changing products and different camera angles. The system could also be replaced with multiple smart cameras located in the assembly line. However buying several smart cameras would cost more than buying one smart camera and one light weight robot. Fixed cameras would also disturb the assembly process as the camera should be close to the products.

4.1 Selected components

AGCO Power has already different kind of machine vision systems installed in the assembly line. Applications vary from sensor and pc-based solutions to smart cameras. The only smart camera model is from Matrox Imaging. The model name is Matrox Iris GT 1900 which already runs on another quality inspection application. Buying a new smart camera from different vendor would increase complexity and make maintaining machine vision programs harder as the programmer should use different kind of software for each application. In addition the Matrox Iris GT offers better resolution in its price class.

Matrox Iris GT communicates directly with other automation equipment through the integrated digital I/Os, Ethernet and serial ports. An Ethernet interface allows the system to communicate over the factory-floor and enterprise networks. These features allow the machine vision system to be completely integrated with the quality gate on the factory floor and quality control on the enterprise level.

Figure 18: Matrox Iris GT smart camera (Matrox Imaging)

Table 5: GT1900 specifications (Matrox Imaging)

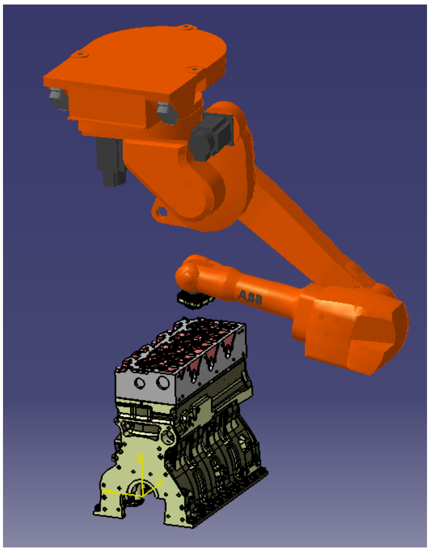
CCD sensor	diagonal 8.9mm (1/1.8”)
Resolution	1600 x 1200
Frame rate	15 fps
CPU	1.6GHz Intel Atom
Volatile memory	1 GB DDR2
Non-volatile memory	2GB flash disk

AGCO Power uses mostly robots provided by ABB in its assembly process. As the designed inspection system is going to be part of the assembly line a consistent choice would be a light weight robot made by ABB. However ABB hasn’t yet launched its light weight robot that could share the workspace with a human. A non-compliant light weight robot could be used in a case where compliant LWRs reach wouldn’t be enough. The second choice is to select a compliant LWR. A diesel engine is quite huge product which set some limitations: a robot has to have a great reach. Compliant LWRs are quite small and the arm reach is most of the time less than 1000 mm. However the Universal Robots’ UR 10 has a reach of 1300 mm. The suitability of UR 10 was tested in Delmia where a 3D model of inspection site was built and the reach of UR 10 was tested.

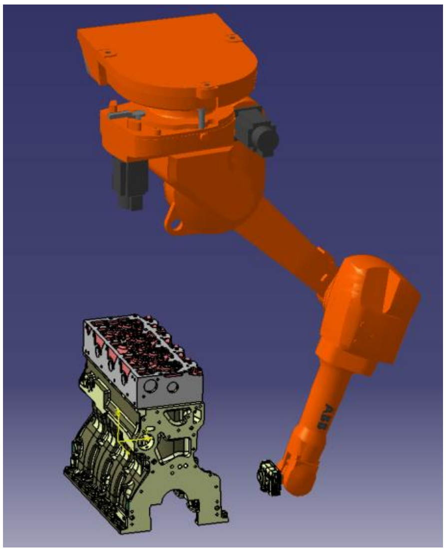
4.2 Layout of the designed system

The inspection system has mainly two options: the system can be added to an existing quality gate where a human works at the same time or it can be added to assembly line as a new work phase. The first option requires a compliant robot while the second option could be non-compliant. The inspection task can be divided to manual and automatic inspection. Both of them can be performed individually why the separation of them might be useful. Even though a compliant robot allows a human presence it doesn’t mean they should be working on the same object at the same time if the assembly process or inspection doesn’t require it. The robot could slow down manual inspection as a worker should follow robot’s movements. This might cause problems depending on the phase time. The inspection time is depended on the amount of features and their complexity as advanced search methods require more time than simple methods. The current production speed shouldn’t set any limitations for the system. The following layout is designed for an application where a robot has its own work station in which a human presence is allowed.

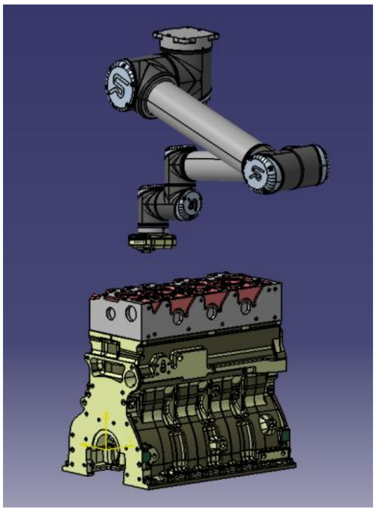
Most of the features to be checked are located on the top or on the sides of a diesel engine. Mounting the robot above the object allows a better working area and the robot can reach required positions easily. Working on the edge of working area sets some limitations which could prevent achieving an optimal camera angle in some cases. In addition a roof mounted robot saves space on factory floor. A human can then freely walk around the diesel engine while the robot works on the top. The Figure 18 shows IRB1600s and UR 10s images about the reach study.



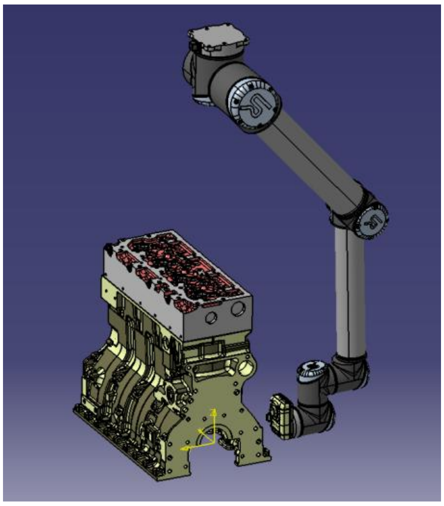
IRB1600 top



IRB1600 side



UR 10 top



UR 10 side

Figure 19: Reach study of IRB1600 (reach 1450mm) and UR 10 (reach 1300mm). Note: the diesel engine model is not finished product.

The reach study revealed that IRB1600s reach of 1200mm wasn’t enough for the application. Even a different model with better reach (1450mm) had problems achieving the top area of the diesel engine. The configuration of IRB1600 doesn’t allow folding into small space which leaves part of the top area uncovered as the robot has to work near work space borders. However the UR 10 can be folded into smaller space which allows robot to be installed closer to the engine. Rough simulation with unfinished diesel engine model shows that the UR 10 could fit for the application.

4.3 Integration with assembly process

Inspection process should be integrated into assembly process in a way that it increases the content of the work. This is completed with various visual, interactive and automatic features. The smart camera passes the information to the next work station where the manual inspection is completed. At the quality gate a worker can read a report created by the smart camera from an interface that is part of the assembly process control software (Keko). If the inspection has been successful with no defects a worker will check out the result and continue its work normally. In case of an error or defect an inspector has to check the result manually.

The work is done manually by operating a touch screen which runs Keko. The worker should get visual instructions which point the defect area on a product. Visual instructions will make the inspection task easier as the feature can be located fast. In addition it reduces the risk of inspecting a wrong feature.

Each of the defects is classified and requires a reason code for the quality control. In most cases the smart camera can define the reason or suggest it. Such reason codes could be for example “part missing”, “wrong orientation” or “wrong part”. The inspector then has to only accept the reason code or chance it if it is another type of defect. The reason code also helps the worker to avoid common mistakes. For example the wrong orientation code tells that the part is most likely assembled but its orientation is wrong. The worker focuses then on the orientation instead of just checking that the part is assembled.

Machine vision software offers usually a way to see the last inspection result. In PC-based solutions this means usually a window showing the last camera image. In smart camera applications the software runs inside the camera and the system doesn’t have its own pc. The inspection result and image can be linked in most cases to any pc with web browser technology. For example Matrox Design Assistant can send the last inspection result and image into a web browser running at the work station. A worker can check the image and see what features have failed in the inspection process. This can help in the manual inspection as the work knows what has caused the inspection process to fail and which features should be checked.

In some cases it might be useful to repair detected faults before manual check. If a fault prevented full manual check at quality gate the smart camera could be used to rework routes. A faulty product could be sent directly to a repair station where the problem would be fixed. Afterwards the product would proceed normally and continue to a quality gate. The rework of routes should not be the first choice as most of the defects can be fixed at quality gate. The product should head to a repair station only if the fixing at quality gate is not possible or if the defect prevents a manual inspection.

4.4 Illumination

Illumination is a critical component that can ruin the system if it is not well designed. If the contrast between desired features and background is poor the system will be most likely unstable causing lots of false errors. Even if the problem occurs only with some features it will question the reliability of whole system. By investing in proper illumination a successful application can be created.

Test images taken with Iris GT1900 showed that the background light can barely illuminate a diesel engine. As a result a diesel engine has to be illuminated with other light sources. Fixed light sources around the inspection scene might not be enough as a robot, a camera and a diesel engine itself could create disturbing shadows. One option is to attach a light source around the camera. The desired angle for lighting would then be the same as the desired camera angle.

General lighting techniques in machine vision applications are bright field, dark field, back lighting and diffuse lighting. (National Instruments 2010) In the test images a LED Ring Light (bright field) was used. The bright field technique generated some problems on curved surfaces and flat surfaces. The picture 19 below demonstrates this problem.

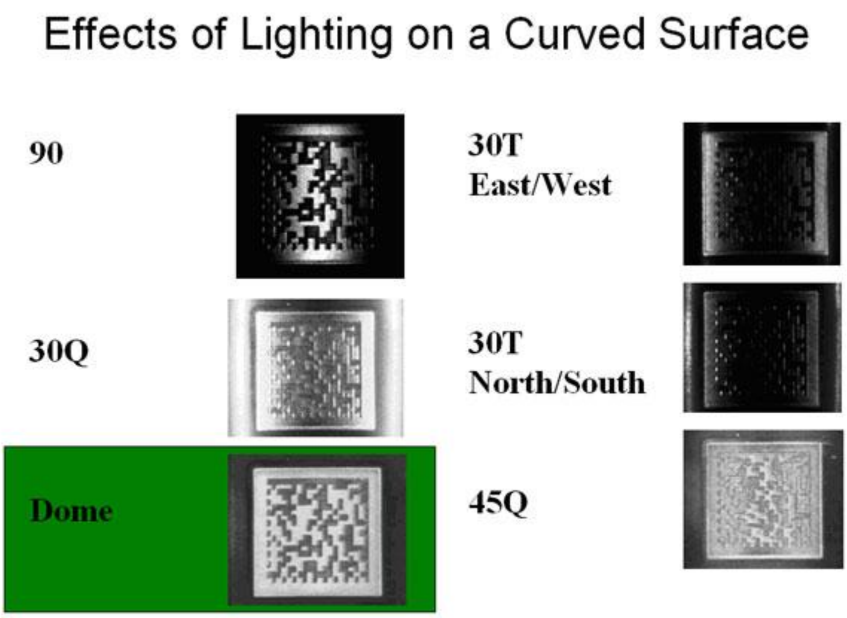


Figure 20: Different lighting angles on a curved surface (O'Brien 2006)

In the Figure 19 one can see how different lighting angles affect the resulting image. In bright field (90) only the mid area is visible because only that area reflects light back. In dark field (30) technique the mid area is left too dark and the light reflects back to camera only from the sides. In general choosing a wrong lighting technique leads to a situation in which some of the areas are too bright, too dark or the contrast between the feature and background is insufficient.

A diesel engine has flat and curved features that need to be checked. Most of the components and features have shiny surfaces that reflect light well. The bright field method isn’t the best choice because of reflections from these surfaces. The background lighting doesn’t work for this application either. The best option in this case is diffuse lighting. Diffuse lighting can be created with dome or on-axis diffuse and they need usually a close proximity to the sample. Dome light could be attached to the robot end-effector along with a smart camera.

4.5 Considerations

Matrox Iris GT1900 is an advanced smart camera and it provides all the tools required in inspection task. Investing in more expensive model is not recommended as the resolution is good enough. The lighting conditions is the key component in this application and buying wrong kind of light source will most likely cause problems. Dome lighting is most likely the best choice for this application as it suits for both flat and curved surfaces. The test images and the theory both support this. Most of the features are also quite small requiring camera to be close to a product. This suits well for a dome lighting as it requires small distance from an object.

Although compliant robots can work with a human it might be much simpler to install the application next to the quality gate. Choosing a classical industrial robot has some drawbacks as it requires more space and external safety equipment. Most of the compliant robots are light weight and they can be moved easily. Classical industrial robots require more work when their location has to be changed. The light weight robot can also be folded due to its structure allowing a better reachability than a classical industrial robot with the same reach.

5 MACHINE VISION PROGRAM

Building a complete machine vision program will be a complex task as the production process has several different variants. This affects also the machine vision program and its structure. In this chapter the structure of inspection program and examples of inspection tasks are presented. The chapter works as a documentation how the complete machine vision program could be created for the system and what should be taken into account when setting up an inspection. There are several ways to build up the whole program and this work presents only one.

5.1 Program structure

Matrox Design Assistant uses the flowchart method that is a universally accessible recognized and understood method of describing the sequence of operations in a process. In Matrox Design Assistant a flowchart is put together using a step by step approach where each of the steps is taken from an existing toolbox. The program structure can be divided into following steps: program selection, inspection and decision making. The Figure 20 presents the general structure of the program.

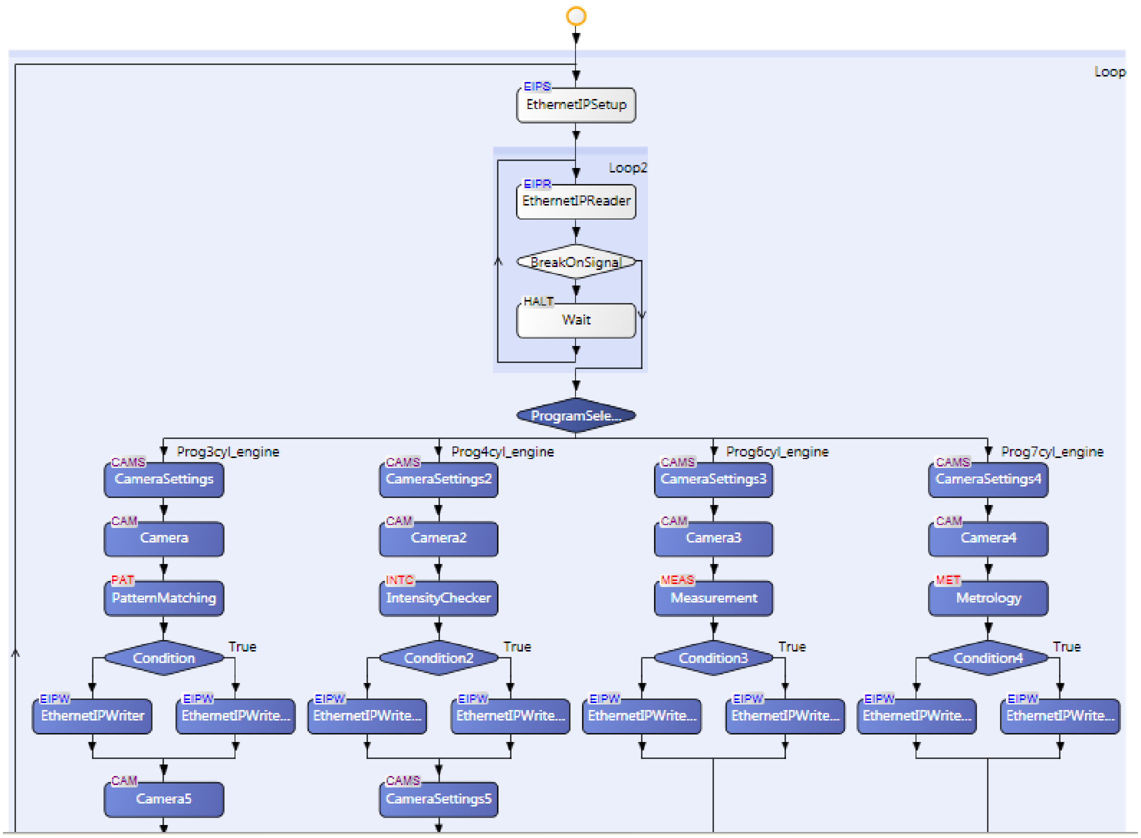


Figure 21: Program structure of the machine vision system

The program starts with the program selection. The smart camera receives product information through network which defines the program that should be completed. Production control software can be considered as the master in this application as it tells to the robot and the smart camera which program should be executed. During the inspection process the communication occurs only between the smart camera and the robot. To reduce the amount of interfaces needed the robot can deliver the program information to the smart camera.

Once the robot has received information it moves to the location where the camera takes the first image. At the location the robot sends a trigger signal to the smart camera. The smart camera then captures an image and processes the image. Meanwhile the robot moves to the next location the smart camera derives information from the image and makes a decision whether the feature is ok or no. The result is then forwarded to the robot. The robot stores the inspection results which are forwarded to production control software once all features have been checked. The incoming result is also a signal from the smart camera that the smart camera is ready to capture a new feature. Depending on the used machine vision tools the smart camera should be able to inspect features during robot movements.

Decision making can include only sending ok- or not ok-signal. In case of a defect the smart camera can be programmed to send more data about inspected features. Such features could be for example a number of occurrences found, orientation information, length information etc. Passing more information about inspected features can help in manual inspection as a worker has more information about a possible defect.

5.2 Program selection via Ethernet

The smart camera has to receive product information either from robot or production control software. With the information a smart camera is able to select right inspection program depending on a product variant. The Figure 21 presents how the program selection is programmed.

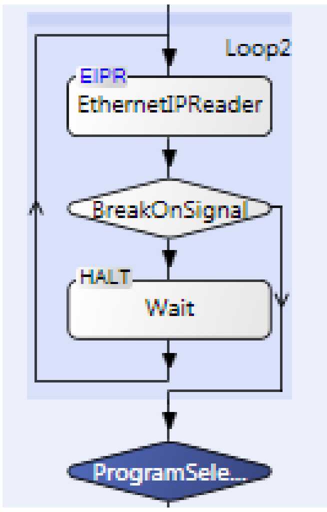


Figure 22: Structure of EthernetIPReader polling loop

The program selection is done with a polling loop where the EthernetIPReader step tries to read information. If the signal is missing the loop continues with a wait command. The loop breaks only when the signal is received. The program continues then with the Switch-step (ProgramSelection) which guides the program to the right branch.

5.3 Inspection

The structure of inspection is the same regardless of the feature being inspected. The inspection begins with loading camera settings that has an effect on the quality of image. For example by adjusting exposure time the lighting can be modified. Camera settings should be loaded before capturing an image and before triggering. This minimizes the delay between trigger command and image capturing. Loading camera settings is required only in the beginning of the program. Otherwise camera settings remain the same until new settings are loaded.

The next step after loading camera settings is to wait for a trigger signal from the robot. The idea with trigger loop is the same as it is with the EthernetIPReader loop. The loop doesn't break until the signal is received. Once the signal is received the smart camera captures an image. The captured image can be stored on smart cameras internal hard disk or on a network drive. Storing images is optional and it can be helpful when setting up an inspection system or when sample images have to be collected.

Another optional step after image capturing is image preprocessing. This is only necessary when the lighting conditions don't meet requirements resulting with a poor contrast between the inspected feature and background objects. As the system has to be able to check several different features with the same lighting the need for preprocessing tools arise. The step should be considered as the last option as camera angle, lighting and exposure time should be optimized first.

The captured image is then analyzed with measuring tools that are able to extract specific information from the image. The information can contain measurement information such as number of occurrences found, length, angle, contrast value etc.

5.4 Inspection task examples

To demonstrate that the designed application could be implemented successfully a series of test images were taken with Matrox Iris GT1900 smart camera. The test images gave also valuable information about lighting conditions at the quality gate. Each example includes a sample image and description of the tool used to carry inspection.

5.4.1 Rubber pads

The first example is "rubber pads" which are assembled to protect a diesel engine during transportation. The number of pads assembled varies between zero and four depending on the product variant and the customer. Pattern matching method was used to search for similar features in the picture. The Figure 22 presents images from the same engine. The only difference between images is that part of the pads has been removed.

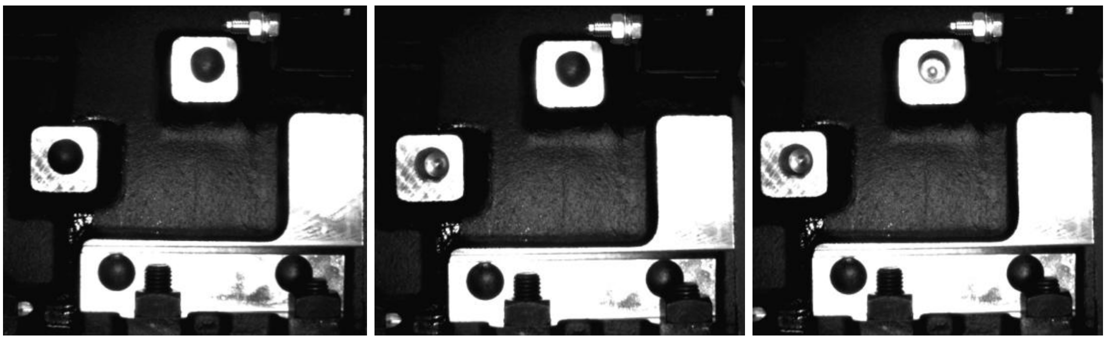


Figure 23: Sample images of rubber pads. Four pads on the left, three pads in the middle and two pads on the right.

The bottom right pad is partly covered by a bolt. This part was used as a model when teaching the feature. The bolt and other dark areas were masked from the model.

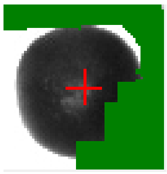


Figure 24: Taught model of rubber pad.

The smart camera was able to find the correct number of occurrences in all test images taken. The lowest score was over 80.

5.4.2 Dipstick / oil stick

Dipstick has short and long versions and both of them have a few variations that differ only a little bit from each other. The most distinct feature is the color dipstick. The smart camera can detect the color of a dipstick and tell whet ever the stick is right or not. Although the sample images were taken with a grayscale smart camera the color of the stick can be figured out with the intensity of dipstick. The tool used was IntensityChecker that calculates the intensity within the specified area. The tool can detect minimum, maximum, average intensity and contrast in the area. The Figure 24 presents sample images from different dipsticks.

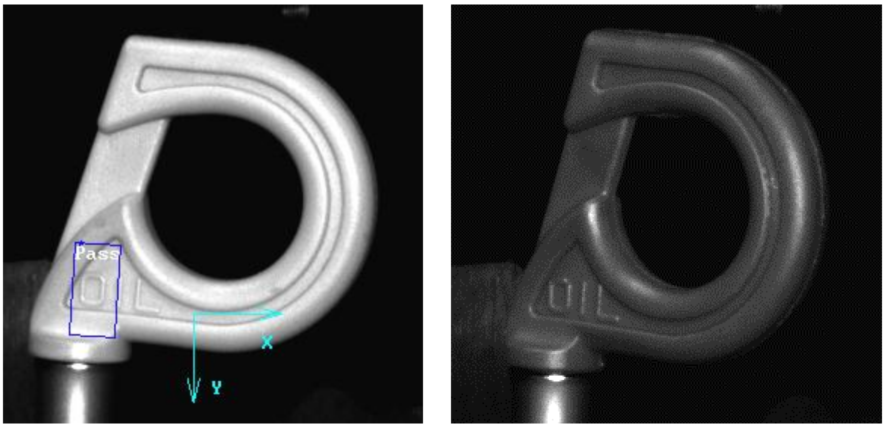


Figure 25: Sample images of dipsticks: yellow on the left and orange on the right.

The hole for dipstick is always at the same position and the intensity is measured from the area above this. This area covers only the part of the dipstick but this prevents any failures due to varying orientation of dipstick. The intensity was measured from different locations because the shadows make a small impact on the result. The effect on average intensity is however very small (+/- 5 from average intensity).

Table 6: Intensity of different dipsticks.

Color	Average
Orange	65.3
Brown	36.1
Grey	254.9
Green	83.9
Yellow	201.0

The difference between average intensity is good and a smart camera can tell from the average intensity if the stick is correct or not. Falling outside from the specific range would lead to a failed inspection result in this case.

5.4.3 Angle of turbocharger

Some models require a specific angle for turbochargers. Otherwise the assembly at customer isn’t possible or it becomes very hard. A human worker can’t detect or measure this angle easily. With Metrology tool a smart camera can measure the angle of a turbocharger. With Metrology tool a segment of image can be analyzed. In this case the tool looks for a line where white turns to black. The Figure 25 presents a sample image from one turbocharger.

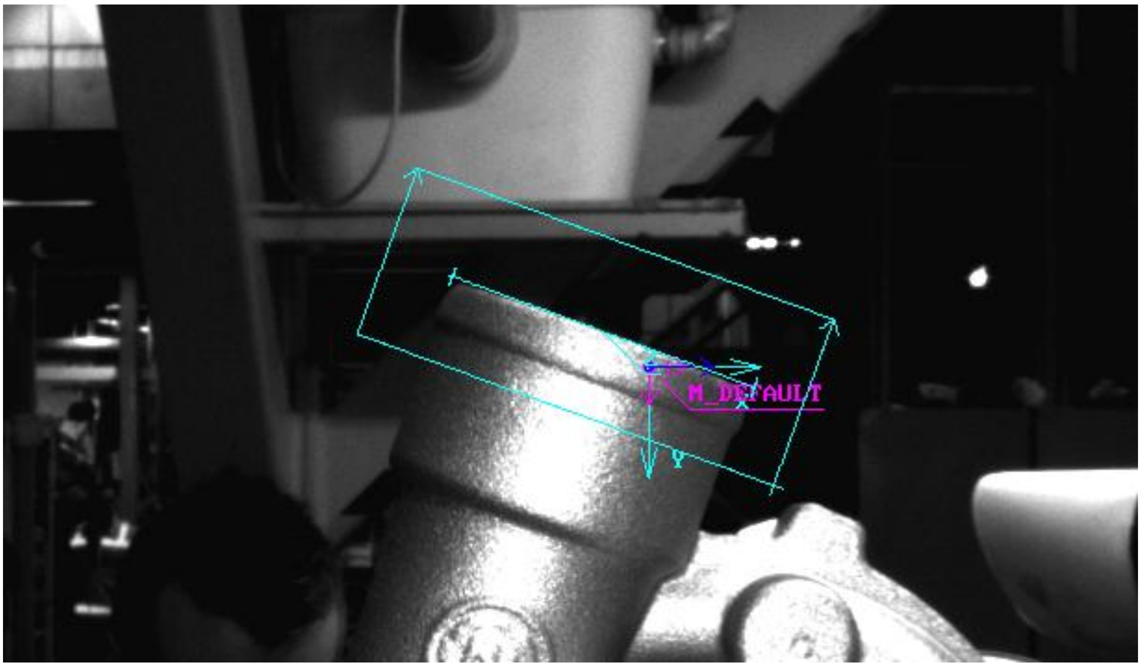


Figure 26: Measured line of a turbocharger.

Angle of the line can be compared to given tolerances in the same step. The tool is reliable and it can draw a decent line on the surface of a turbocharger. However the positioning of the smart camera is very important as it can cause a significant error in the result. If the camera is located below a turbocharger (or the line) the result is most likely incorrect as the line is drawn in a wrong way. The background of the image can also cause an error. Using an optical filter and specific light wavelength prevents any disturbances from the background light.

5.5 Considerations

Each program has its own inspection tasks that depend on the product information. Chances in one program don't affect other inspection programs unless they are supposed to use the same program. Using the same program for multiple product variants works as long as they check exactly same features with same properties. When chances have to be made it is highly recommended that a new program will be created for a product variant.

Although it's possible program production control software to communicate directly with a smart camera it might be easier to communicate through a robot. In this way a production control software doesn't require two interfaces for the application. The second issue supporting this design is a communication between the robot and the smart camera. The smart camera has to send a signal that an inspection task is over and it's ready for a new inspection task. Otherwise the robot might trigger the signal too early and a smart camera might miss the trigger signal.

6 SUMMARY

Quality inspection or visual inspection covers a wide variety of tasks and most of them can be automated successfully. By automating these inspection tasks the quality and productivity can be improved as a human will free from boring and repetitive inspection tasks. A worker will become fatigued and de-sensitive after checking the same feature multiple times. Another reason for automatic quality inspection is data logging. Manual data logging includes a possibility of an error as it is likely to occur on the long run when done manually. In addition automatic data collection is a better option for SPC.

Choosing right components for the machine vision system is critical. For example, by choosing a wrong illumination method the whole system might become unreliable. DoFs of the system are also affected by the selected components. Placing the camera on the robots end effector increases the flexibility by allowing several different poses and different size of objects to be inspected. Designing a machine vision system is usually a trade-off between flexibility, complexity and cost.

Light weight robots are a new generation of torque-controlled robots developed for application areas different from the classical industrial robots or where the use of industrial robot is not applicable. Their structure and control methods usually allow human presence in the shared workspace with certain limitations. Simulations made with Delmia revealed that a classical industrial robot located on the top of a diesel engine couldn't reach the same positions as a light weight robot although their reach was almost the same. The reason for this lies in the structure of light weight robot as most of them can be easily folded allowing bigger workspace within its reach. The structure of the light weight robot also allows relocation making the light weigh robots an ideal choice if the robots place has to been changed frequently. The light weight robots ability to be easily reprogrammed by hand guiding makes them suitable for small batch sizes. This productivity zone is located between manual and fixed robot automation zones where the use of manual assembly is too expensive and fixed robot automation is considered not yet profitable.

Test images taken from diesel engine models showed that the automatic inspection system could be implemented. Some of the features can be easily detected while some features could cause problems if the improper illumination was selected. With proper illumination even difficult cases could be inspected. The system doesn't require huge investment and it could certainly improve quality by detecting defects and by easing the workload of a human worker.

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